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PREDICTION OF THE ANNUAL CYCLE OF TEMPERATURE CHANGES IN A STRATIFIED LAKE OR RESERVOIR: MATHEMATICAL MODEL AND USER'S MANUAL

Patrick J. Ryan, et al

Massachusetts Institute of Technology

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RALPH M. PARSONS LABORATORY
FOR WATER RESOURCES AND HYDRODYNAMICS

Report No. 137

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FOREWORD

This is the fourth report issued in conjunction with a continuing research program on thermal stratification and water quality in lakes and reservoirs. The previous reports are as follows:

1. Dake, J.M.K. and D.R.F. Harleman, "An Analytical and Experimental Investigation of Thermal Stratification in Lakes and Ponds", M.I.T. Hydrodynamics Laboratory Technical Report No. 99, September 1966. (Portions of this report have also been published by the same authors under the title: "Thermal Stratification in Lakes: Analytical and Laboratory Studies", Water Resources Research, Vol. 5, No. 2, April 1969, pp. 484-495.)
2. Huber, W.C. and D.R.F. Harleman, "Laboratory and Analytical Studies of the Thermal Stratification of Reservoirs", M.I.T. Hydrodynamics Laboratory Technical Report No. 112, October 1968.
3. Markofsky, M. and D.R.F. Harleman, "A Predictive Model for Thermal Stratification and Water Quality in Reservoirs", M.I.T., Department of Civil Engineering, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Technical Report No. 134, January 1971.

This report is intended as a user's manual for the transient temperature distribution model developed in the second report (Technical Report No. 112). The computer program presented herein supersedes that given in Technical Report No. 112. The numerical scheme has been changed from an implicit to an explicit scheme. Other changes include the option of accounting for the travel time of inflows within the reservoir, simultaneous or intermittent withdrawal from multi-level outlets in the reservoir and the continuous variation of the water surface elevation. The emphasis in this report is placed on an explanation of the computer program rather than on the development and testing of the theory.

ABSTRACT

The annual cycle of temperature changes in a lake or reservoir may be quite complex, but predictions of these changes are necessary if proper control of water quality is to be achieved. Many lakes and reservoirs exhibit horizontal homogeneity and thus a time-dependent, one-dimensional model which describes the temperature variation in the vertical direction is adequate. A discretized mathematical model has been developed based on the absorption and transmission of solar radiation, convection due to surface cooling and advection due to inflows and outflows. The mathematical model contains provision for simultaneous or intermittent withdrawal from multi-level outlets and time of travel for inflows within the reservoir. Heat transport by turbulent diffusion in the hypolimnion is neglected.

Good agreement has been obtained between predicted and measured temperatures in both the laboratory and the field. Field verification consisted of the simulation of the thermal structure of Fontana reservoir during a nine-month period. Criteria for the applicability of the model are given. The mathematical model is a predictive one, since the required data is that which would normally be available before the construction of a reservoir.

Emphasis has been placed on a detailed explanation of the physical basis for the mathematical model and on the computer program inasmuch as the report is intended primarily as a user's manual.

ACKNOWLEDGEMENT

This investigation was supported, in part, by the Federal Water Quality Administration, Department of the Interior, under Research Grant No. 16130 DJH entitled "Thermal Stratification and Reservoir Water Quality". The project officer was Mr. Frank Rainwater, F.W.Q.A. Pacific Northwest Water Laboratory, Corvallis, Oregon.

A portion of the laboratory experiments were carried on in 1967 by Dr. Wayne C. Huber, then a graduate research assistant in the Hydrodynamics Laboratory. Computations were made at the M.I.T. Information Processing Service Center.

The authors wish to express their appreciation to Mr. Rex A. Elder, Chief of the Engineering Laboratory Branch of the TVA Division of Water Control Planning and to Dr. W. O. Wunderlich for their cooperation in supplying the field data for Fontana Reservoir. Funds for publication of this report were provided jointly by the TVA Division of Water Control Planning, Reed A. Elliot, Director, and the Cabot Solar Energy Fund established at M.I.T. by Godfrey L. Cabot.

Our thanks to Miss Kathleen Emperor who typed the report.

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1. Introduction

1.0 Thermal Stratification in Reservoirs

Thermal stratification occurs in almost all lakes and reservoir impoundments. In shallow "run of the river" reservoirs the stratification may be relatively weak and in certain seasons the isotherms may be tilted in the downstream direction. In deep lakes and in reservoirs in which the storage volume is large compared to the annual through-flow, the isotherms are horizontal during most of the year and strong stratification is generally developed during the late summer and autumn seasons. The mathematical model developed in this study is concerned with the latter situations in which the water temperature is a function of depth and time.

The primary causes of thermal stratification are the low thermal conductivity of water, the limited penetration of radiant heat and light, and the fact that stream inflows in late spring and early summer tend to be warmer than the reservoir surface waters. These warm inflows spread out over the reservoir surface. Furthermore, virtually all heat, apart from advected heat, enters the reservoir through the surface in the form of radiant energy. A large percentage is absorbed in the first few meters and thus the water near the surface is heated more quickly than that in the lower layers. This warm water tends to remain at the surface, absorbs more heat, and thus a stable condition tends to be set up. However, evaporation will always cool the surface layer, setting up convection currents. Surface cooling and hence convection will be enhanced by back radiation and conduction losses, especially at night. Wind stresses on the water surface will cause mixing whenever a neutral or unstable density gradient is set up by surface cooling. These processes of heating, cooling, and wind action lead to the development of a warm, freely circulating, turbulent upper region, called the epilimnion. This overlays and to a great extent insulates a colder, relatively undisturbed region called the hypolimnion. The generality of thermal stratification in temperature climates has been established since the end of the 19th century (Hutchinson (13)).

A typical annual thermal cycle in a reservoir is illustrated in Figure 1.1 which shows the nearly isothermal condition in early spring, the development of thermal stratification in spring and summer, and the return to the initial condition in winter. The destruction of thermal stratification is accompanied by vertical mixing throughout the reservoir, and is usually referred to as the overturn.

Under thermally stratified conditions, with the hypolimnion insulated from the atmosphere by the epilimnion, renewal of oxygen in the lower layers cannot take

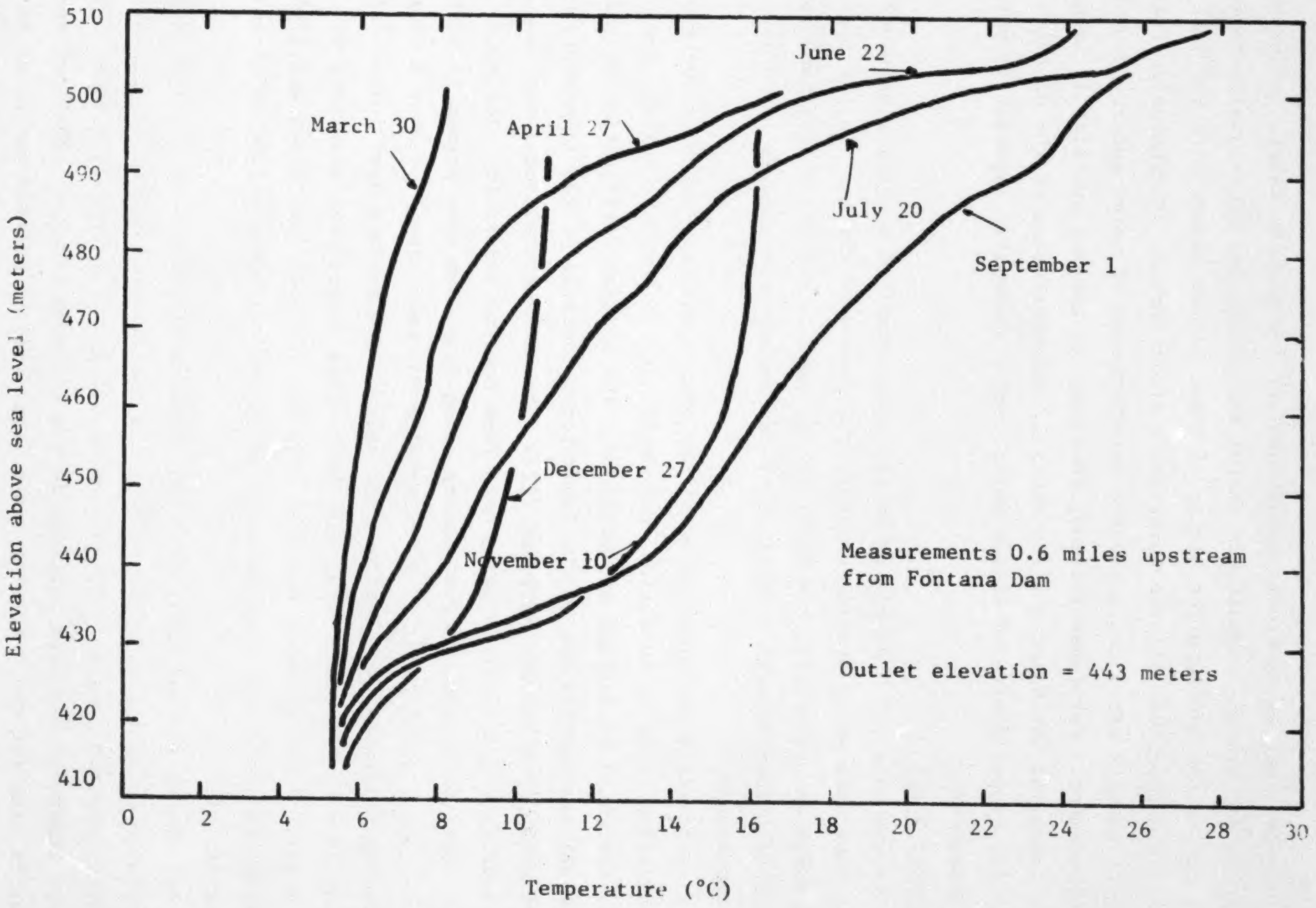


Figure 1.1 Seasonal Variation of Temperature Profiles in Fontana Reservoir, 1966

place. This can lead to anaerobic conditions and low quality water. Anaerobic decomposition may produce undesirable tastes and odors, and occasionally toxic effects. During the overturn the mixing of these bottom waters with the rest of the reservoir may pollute all the water for a short period. Furthermore, release of this poor quality water could cause a deterioration of water quality downstream of the impoundment. For these reasons, knowledge of thermal profiles in impounded waters is essential for water quality control, and prediction of the profiles is necessary for proper design of outlet works, and a systematic approach to water quality management.

1.1 Proposed Model

The emphasis has been placed on the development of a predictive model which uses only such data as is available before the reservoir exists. In the case of existing lakes or reservoirs, the model can be used to predict future behavior under various meteorological conditions or due to man-made changes in inflow and/or outflow conditions.

A discretized mathematical model has been developed, based on the absorption and transmission of solar radiation, convection due to surface cooling, and on a realistic treatment of inflows and outflows. The initial verification of the mathematical model was carried out in the laboratory. Details of the laboratory physical model are given by Huber and Harleman (12). The mathematical model was then extended to the field case and verified using data from Fontana Reservoir. The model has also been verified by other investigators using data from Lake Norman in North Carolina (23). The thermal behavior of reservoirs has been simulated over a complete year allowing for inflow and outflow, and calculating surface heat losses daily as a function of meteorological data, and the surface temperature generated by the mathematical model. Good agreement has been obtained for both laboratory and field cases. The mathematical model has been extended to include withdrawal from multi-level reservoir outlets.

The annual thermal cycle of lakes, with little inflow or outflow, has also been simulated using a simplified form of the model. This option is available in the present computer program. The option of using the mathematical model for a laboratory reservoir has been retained in the computer program. Wherever specific allowance is made for the laboratory case, this will be pointed out so as to avoid confusion.

2. Description of Physical Basis of Model

2.0 Introduction

A comprehensive temperature prediction model must account for internal radiation absorption, boundary heat sources and sinks, and heat transport by advection, convection and diffusion. The geometrical simplifications and assumptions leading to the development of a comprehensive mathematical model will be presented. The important characteristics of the model are discussed and the equation governing the temperature distribution $T(y,t)$ in a stratified reservoir will be derived.

2.1 Schematization of Reservoirs

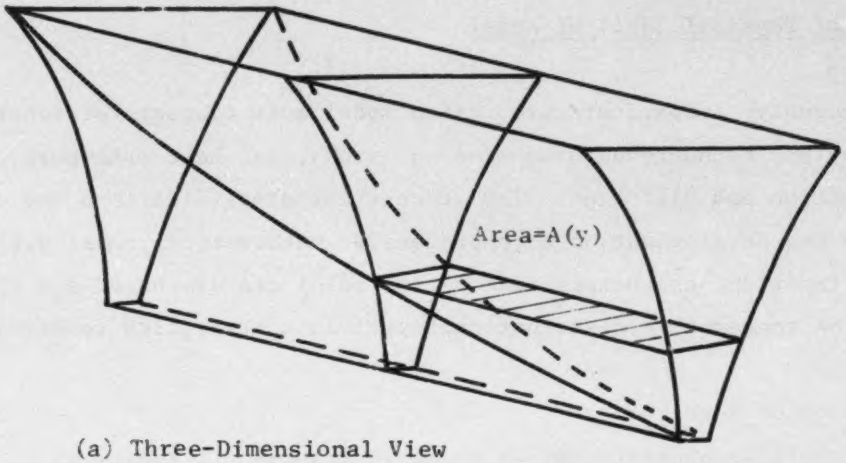
The reservoir is schematized, as shown in Figures 2.1 a,b,c, by considering it as a series of horizontal elements similar to that in Figure 2.2. The element at elevation y has a horizontal area $A(y)$ and thickness Δy. A portion of the river inflow enters the element at the upstream end, and a portion of the outflow through the dam leaves the element at the downstream end. Heat also enters the element through the horizontal surface by transmission of radiation, by vertical advection and by diffusion. The equation governing the temperature distribution will be formulated by considering the conservation of mass and heat within a typical element. However, before this can be done it is necessary to make certain simplifying assumptions, and to consider the mechanisms of radiation absorption, heat advection, convection and diffusion.

2.2 Assumptions

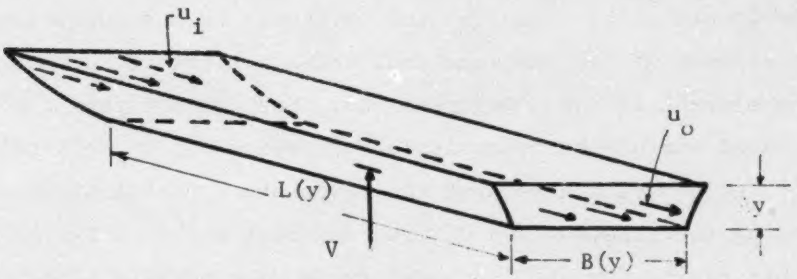
2.2.1 The two principal assumptions involved in the model are:

(a) The isotherms in a stratified reservoir are horizontal, and hence thermal gradients exist in the vertical direction only. This assumption has the effect of reducing the problem from a three-dimensional to a one-dimensional, variable area problem. Observations both in the field and in the laboratory have shown that horizontal isotherms occur in many lakes and reservoirs. However, this assumption limits the applicability of the model, and certain criteria should be satisfied before using it. These criteria are discussed in Chapter 5.

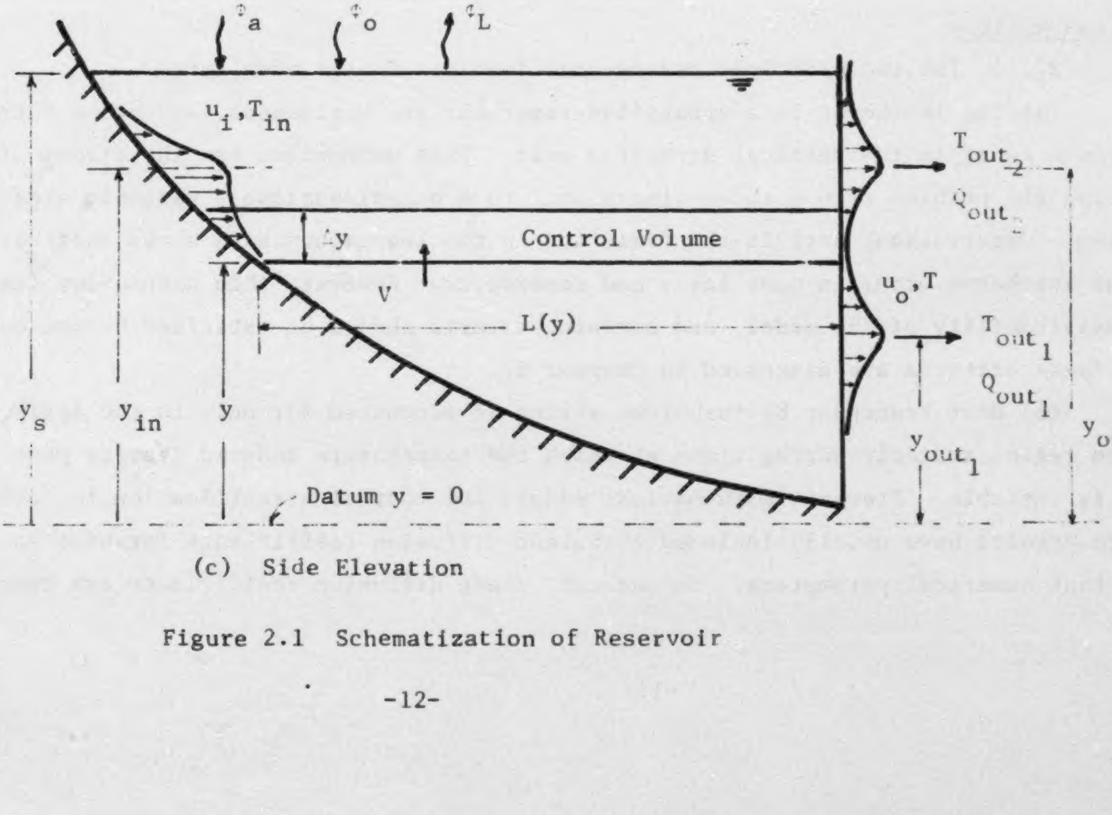
(b) Heat transport by turbulent mixing is accounted for only in the epilimnion region and only during times at which the temperature induced density profile is unstable. Previous mathematical models for thermal stratification in lakes and reservoirs have usually included turbulent diffusion coefficients for heat as important numerical parameters. In general, these diffusion coefficients are functions



(a) Three-Dimensional View

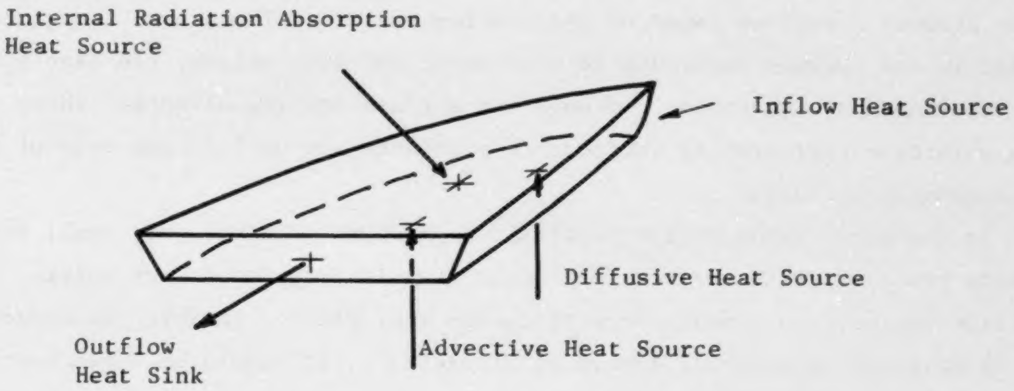

u_i
u_o
L(y)
V
y
B(y)

(b) Control Volume Slice


Φ_a
Φ_o
Φ_L
u_i, T_{in}
T_{out_2}
Q_{out_2}
Δy
Control Volume
V
u_o, T
L(y)
T_{out_1}
Q_{out_1}
y_s
y_{in}
y
y_{out_1}
y_{out_2}
Datum y = 0

(c) Side Elevation

Figure 2.1 Schematization of Reservoir


Internal Radiation Absorption
Heat Source
Inflow Heat Source
Diffusive Heat Source
Outflow
Heat Sink
Advective Heat Source

Control Volume Illustrating Heat Conservation

Figure 2.2 Control Volume

of depth and time, and since these functional relations cannot be specified a priori, such mathematical models tend to lose their predictive value. For any given model it is always possible to find turbulent diffusion coefficients which will match field data. However, it is difficult to determine to what extent these coefficients represent diffusion or merely the effect of simplifications or inaccuracies in the basic formulation of the mathematical model.

The temperature prediction model developed in this study does not require assigned values for turbulent diffusion coefficients. Whenever the temperature profile in the epilimnion develops an unstable density gradient, vertical mixing is induced to produce a surface layer of uniform temperature. Thus, even though turbulence may exist in the surface layer due to wind shear and wave motion, the heat transfer will be dominated by convection currents and surface cooling effects. These currents tend to eliminate near surface temperature gradients and nullify the role of gradient driven turbulent diffusion.

In the hypolimnion region vertical temperature gradients are small and diffusive heat transport will not be significant even if turbulence does exist. In the thermocline region, the density stratification will tend to inhibit turbulence, although it will not necessarily remove it altogether. It should be noted, however, that calculations of thermal diffusivity in the thermocline region of lakes often give values of the same order as the molecular diffusivity. Examples are given by Hutchinson (13), Orlob (19) and Sweers (26). (See Table 1) These values are obtained by assuming that all heat transport, not accounted for by other methods, takes place by turbulent diffusion. Since vertical advective transport is not considered in any of the above cases, these values are probably too high.

Table 1

Molecular Diffusivity of Heat = 0.0014 cm^2/sec

Lake	Eddy Diffusivity at Thermocline (cm^2/sec)	Reference
Sodon	0.007	Hutchinson (13)
Linsley Pond	0.0033	Hutchinson (13)
Mendota	0.025	Hutchinson (13)
Castle Lake	0.02	Orlob (19)
Ontario	0.02 - 0.07 (seasonal average)	Sweers (26)

The approach adopted in this study is to neglect turbulent diffusion as a first approximation, and to take all other known forms of heat transport into account as accurately as possible. If marked discrepancies occur, which cannot be explained by other factors, e.g., mixing of the inflow as it enters the reservoir, then allowance should be made for turbulent diffusive transport. However, in both laboratory and field reservoirs good agreement has been obtained between predicted and measured temperatures, and thus it appears that this approach is justified.

Since turbulent diffusion is neglected, it would seem only reasonable to neglect molecular diffusion as well. This process is included in the general model for three reasons: 1) Molecular diffusion may be significant in the laboratory case; 2) If accurate values of vertical turbulent diffusivity become available, they may be included in the model at a later date; 3) A numerical solution to the heat transport equation will be presented, and numerical schemes, regardless of type, behave better when diffusion is present. It should be mentioned here that numerical schemes involving advective terms introduce errors which have the same effect as an additional diffusive term. This effect is discussed in Section 3.4.

2.2.2 Other assumptions, less fundamental than (a) and (b) are:

(c) Solar radiation is assumed to be transmitted in the vertical direction only. This assumption is not exact but, due to refraction at the water surface and the fact that when the solar angle is small a large proportion of the short wave radiation comes from the sky, this should not lead to large errors.

(d) The sides and bottom of the reservoir are assumed to be insulated, the only heat crossing the boundaries (apart from the surface) is via inflow and outflow.

(e) The density (ρ), specific heat (c) and the coefficient of molecular diffusivity (α) are assumed constant in all heat budget and heat transport calculations.

(f) Solar radiation energy, transmitted by the water and intercepted by the reservoir sides, is assumed to be distributed uniformly over the cross section at the depth of interception. This effect may be quite significant in lakes and reservoirs, which have both clear water and a rapid change of area with depth near the surface (see Figure 2.3).

2.3 Important Model Characteristics

2.3.1 Variable Area

Variation of area with depth is taken into account. This affects both the vertical advection of heat, and the distribution of the solar radiation energy.

2.3.2 Direct Absorption

Solar radiation is absorbed directly in the body of the fluid, as well as

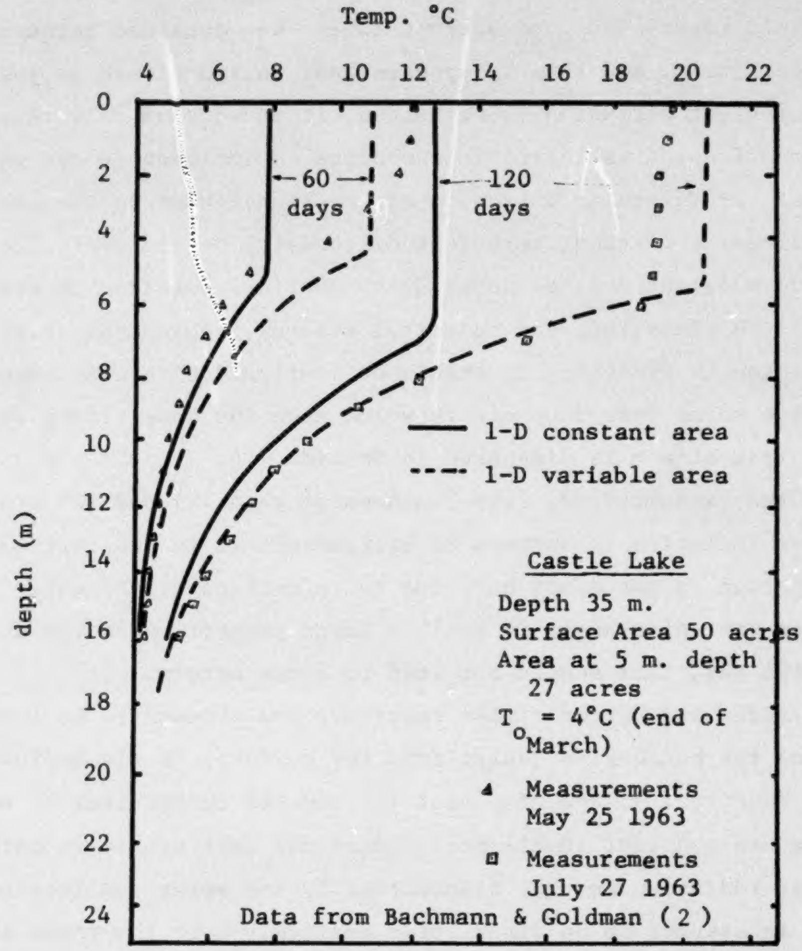


Figure 2.3 Effect of Variable Area on Temperature Predictions in a Clear Lake

at the surface. Transmission of radiation at elevation y is given (as per Dake and Harleman (5)) by

$$\phi(y) = \phi_o (1 - \beta) e^{-\eta(y_s - y)} \tag{2.1}$$

where

y_s = water surface elevation

ϕ_o = net incident solar radiation (gross-reflected)

β = fraction of ϕ_o absorbed at the surface ($\sim$ 0.4 - 0.5)

η = extinction coefficient of reservoir water. η varies for different reservoirs and may also vary in time and space. This flexibility is included in the model. See Figure 2.4 for examples of measured and theoretical curves.

2.3.3 Convection

Convection in the epilimnion is accounted for by allowing mixing to take place whenever the temperature gradient ($\partial T/\partial y$) is negative (y is elevation, positive upwards). Since surface losses (due to evaporation, back radiation, etc.) are generally greater than surface absorbed energy (due to solar radiation, $\beta\phi_o$, and atmospheric long wave radiation) this leads to a mixed zone at the surface in most cases, although in spring and early summer this mixed zone may be rather shallow.

2.3.4 Inflow and Outflow

To include inflow or outflow in heat transport calculations, two separate items of information are required, namely the level of entry or discharge, and the distribution of flow about that point.

It is assumed that inflow enters the reservoir water column at the level at which its density matches that in the water column. If entrance mixing (see Section 2.3.10) is allowed to take place, the mixed inflow temperature is then taken as the criterion. Outflow is assumed to be centered about the level of the outlet. This assumes a linear temperature gradient in the vicinity of the outlet, which may not be the case. However, Elder and Wunderlich (8) point out that even for nonlinear gradients near the outlet, the flow is fairly symmetrical about the outlet centerline.

2.3.5 Calculations of Inflow Velocity Distribution

The fact that warm inflows flow directly over the surface, and dense inflows (whether cold or sediment laden) flow along the bottom is accepted in the literature

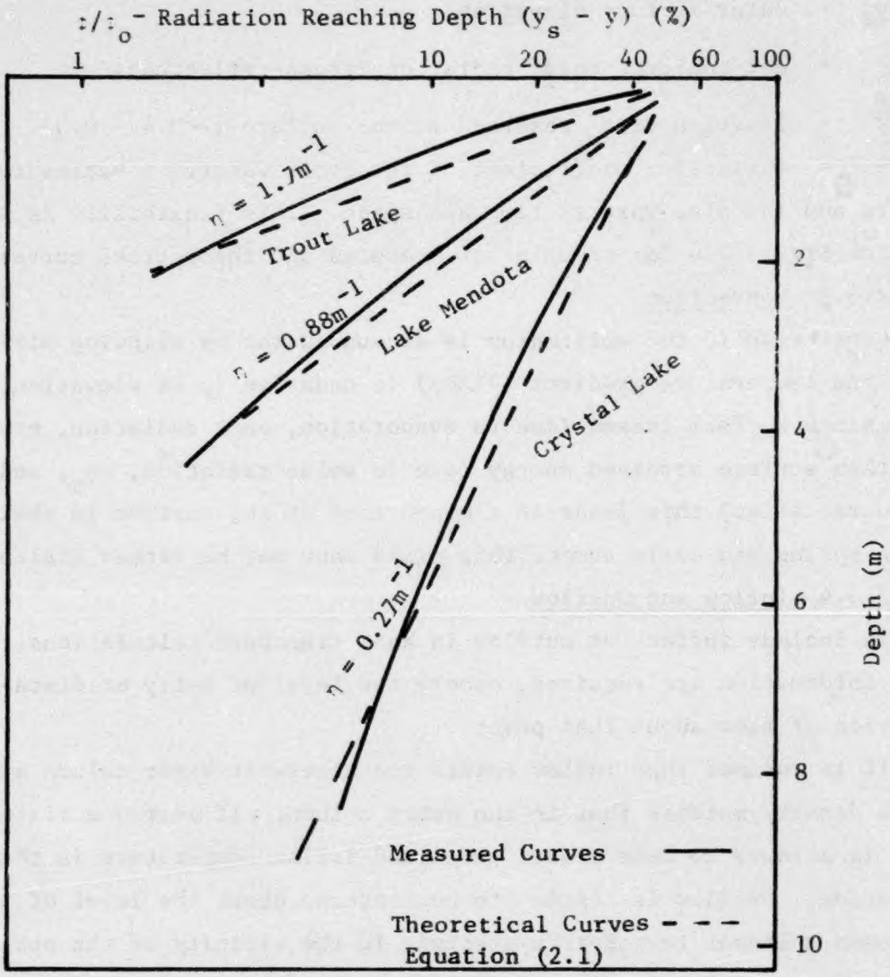


Fig. 2.4 Transmission of Solar Radiation Vs. Depth

on reservoir flows (Howard (11), Goda (10)). However, the evidence for flows at intermediate depth is sparse. Elder and Wunderlich (8) give the results of dye tests in Fontana Reservoir (see Figure 2.5). These dye profiles also show that the inflow velocity profile may be approximated by a Gaussian curve. It is assumed that

$$u_i(y) = u_{i_{max}}(t)\, e^{-\frac{(y-y_{in}(t))^2}{2\sigma_i^2}} \qquad (2.2)$$

where

$u_i(y)$ = inflow velocity at elevation y

$u_{i_{max}}(t)$ = maximum value of the inflow velocity at time t

$y_{in}(t)$ = elevation of inflow at time t

σ_i = inflow standard deviation

Little is known about the value of σ_i. In this model it is held constant and related to the depth of the entering stream.

$u_{i_{max}}(t)$ is found by equating the sum of the inflows into each layer to the total inflow, i.e.,

$$Q_i(t) = \int_{y_b}^{y_s} B(y)\; u_i(y)\, dy \qquad (2.3)$$

where

y_s = surface elevation

y_b = bottom elevation

B(y) = width of the reservoir at elevation y, and can be included in the input data, or as in this case calculated from the horizontal cross-sectional areas and reservoir lengths, i.e., B(y) = A(y)/L(y). This assumes a rectangular basin.

2.3.6 Calculation of Outflow Velocity Distribution

The outflow velocity distribution is treated in a manner similar to that of

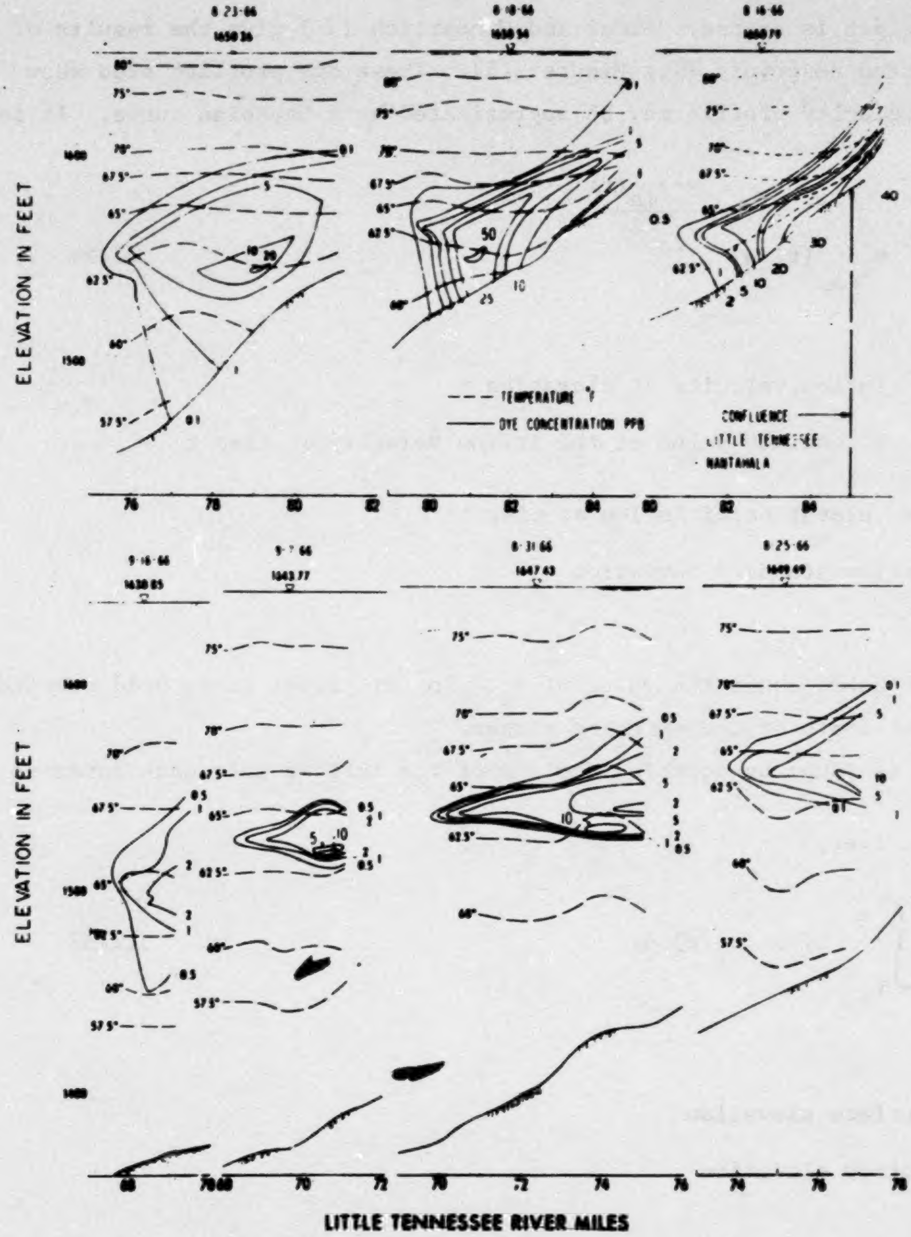


Figure 2.5 Dye Concentration Profiles in Tributary of Fontana Reservoir

the inflow, with one important difference; namely, the standard deviation is calculated using the results of either Koh (16) or Kao (14). The problem of withdrawal from a stratified reservoir is treated rather extensively in the literature. The solutions have been summarized by Brooks and Koh (4). Huber and Harleman (12) also have a rather lengthy discussion of Koh and Kao's work.

2.3.6.1 Laboratory Case

Koh's solution(16)for a steady two-dimensional case involving both viscosity and molecular diffusion is applicable. The thickness of the withdrawal layer δ is given by

$$\delta = \frac{7.14\ x^{1/3}}{(\epsilon g/\alpha\nu)^{1/6}} \qquad (2.4)$$

where

x = horizontal distance from the outlet

ϵ = normalized density gradient, $\frac{1}{\rho}\frac{\partial\rho}{\partial y}$

α = molecular diffusion coefficient

ν = kinematic viscosity

For given values of x, g, α and ν, Eq. (2.4) can be put in the form

$$\delta = \frac{\text{const}}{\epsilon^{1/6}} \qquad (2.5)$$

For the laboratory case, using standard values g, ν, D,

g = 980 cm/sec^2

ν = 0.01 cm^2/sec

α = 0.0014 cm^2/sec

and x chosen at the mid-point of a horizontal line between the outlet and the reservoir bottom (x = 240 cm)

$$\delta = 2.2\ \epsilon^{-1/6} \qquad (2.6)$$

Huber and Harleman (12) note that the operating conditions in the laboratory reservoir were in the range of Koh's experiments, and that the calculated values of δ agreed well with those observed during experimental runs. Equation 2.6 was used in the model verification involving the laboratory reservoir.

2.3.6.2 Field Case

Kao (14) obtained a solution for the case of a diffusionless flow towards a line sink at the bottom of the end of a uniform channel. Huber and Harleman (12) have modified Kao's solution for the unbounded case, and substituted a Gaussian velocity profile instead of the uniform one proposed by Kao. They obtained the following formula

$$\delta = 4.8 \left(\frac{q^2}{g\varepsilon}\right)^{1/4} \qquad (2.7)$$

where q = outflow/unit width, the width being taken as the average width of the reservoir at the elevation of the outlet. This is very close to the formula proposed by Elder and Wunderlich (9), based on some field measurements in Fontana Reservoir. They suggest

$$\delta = 5.0 \left(\frac{q^2}{g\varepsilon}\right)^{1/4} \qquad (2.8)$$

Equation 2.7 has been used in the verification of the model using field data. The units used for the field case were meters, kgms, days, and for these units Equation 2.7 can be written as

$$\delta = 0.0092 \frac{q^{1/2}}{\varepsilon^{1/4}} \qquad (2.9)$$

where

δ = thickness of withdrawal layer (m)
q = outflow/unit width (m^2/day)
ε = normalized density gradient (m^{-1})

The outflow standard deviation, σ_o, is calculated on the basis that 95% of the outflow comes from the calculated withdrawal layer. Thus

$$\sigma_o = \frac{\delta/2}{1.96} \qquad (2.10)$$

and

$$u_o(y) = u_{o_{max}}(t)\ e^{-\frac{(y-y_{out})^2}{2\sigma_o^2}} \qquad (2.11)$$

where

$u_{o_{max}}(t)$ = velocity at $y = y_{out}$ = maximum velocity

y_{out} = elevation of reservoir outlet centerline.

In the above calculations, the density gradient is determined from the temperature gradient at the outlet. Early in the warming period, this gradient may be very small, and may lead to withdrawal over the full depth of the reservoir. However, in many cases a warmed surface layer may have already developed and it is unrealistic to expect this lighter water to be drawn down to any extent. To avoid this, a cut-off gradient has been specified, which limits the thickness of the withdrawal layer. A further refinement could be included which would lead to an asymmetrical withdrawal layer, the asymmetry being a function of the temperature profile on each side of the outlet. This asymmetry was observed in the laboratory reservoir. However, when this refinement was incorporated in the model, no significant improvement was noticed and it has been deleted from the final program.

2.3.6.3 Outlet Geometry

The actual outlet geometry is not usually significant. In the model the outlet appears as a line sink, while in practice it is usually rectangular. However, measurements in Fontana (7) have shown that at a relatively short distance upstream of the dam, withdrawal takes place over the full width of the reservoir. Similarly, as long as the calculated withdrawal layer thickness is large compared to the outlet height, then the latter may be neglected. If, however, the outlet height is similar to, or larger than, the withdrawal layer thickness, then a minimum thickness, say 1-2 times the outlet height, should be postulated.

2.3.6.4 Multiple Outlets

In many reservoirs, withdrawal can take place from several levels. This facility has been included in the mathematical model. The number of outlets, the level of each outlet and the individual outflow rates, are specified in the input data. Withdrawal may take place from one or all outlets at any time. The velocity field of each outlet is calculated as in Section 2.3.6.2, and superimposed on one another. No field verification has been carried out for the multiple outlet case, but the comparison with laboratory results is quite promising. See Figures 2.6, 2.7.

2.3.7 Vertical Advective Velocity

The vertical advective velocity, V, is obtained by requiring that the continuity condition is satisfied at each level. Starting at the bottom element of the reservoir, and setting the inflow across the bottom equal to zero, each element was considered in turn and the vertical velocity calculated so that continuity was exactly satisfied. See Figure 2.8.

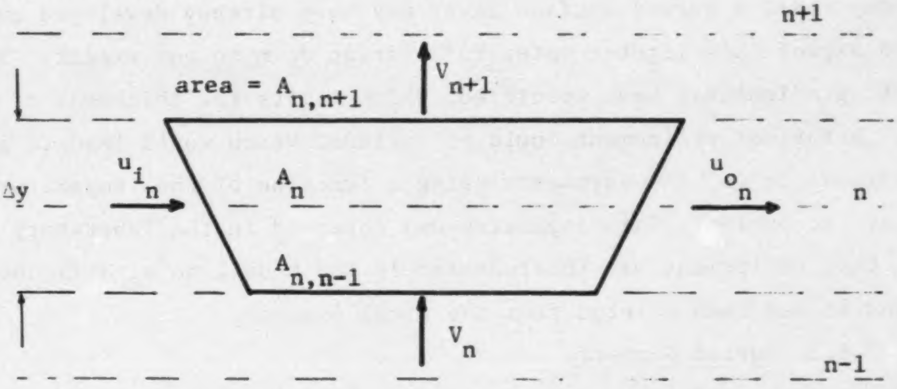


Figure 2.8 Calculation of Vertical Velocity

$$V_{n+1} = \frac{1}{A_{n,n+1}} \left(V_n A_{n,n-1} + B_n \Delta y \left(u_{i_n} - u_{o_n} \right) \right) \qquad (2.12)$$

2.3.8 Travel Time for Inflows

In previous field and laboratory studies it was observed that the measured values of outlet temperature lagged the predicted values. The most obvious cause is that some time elapses between the time the inflow enters the reservoir and the

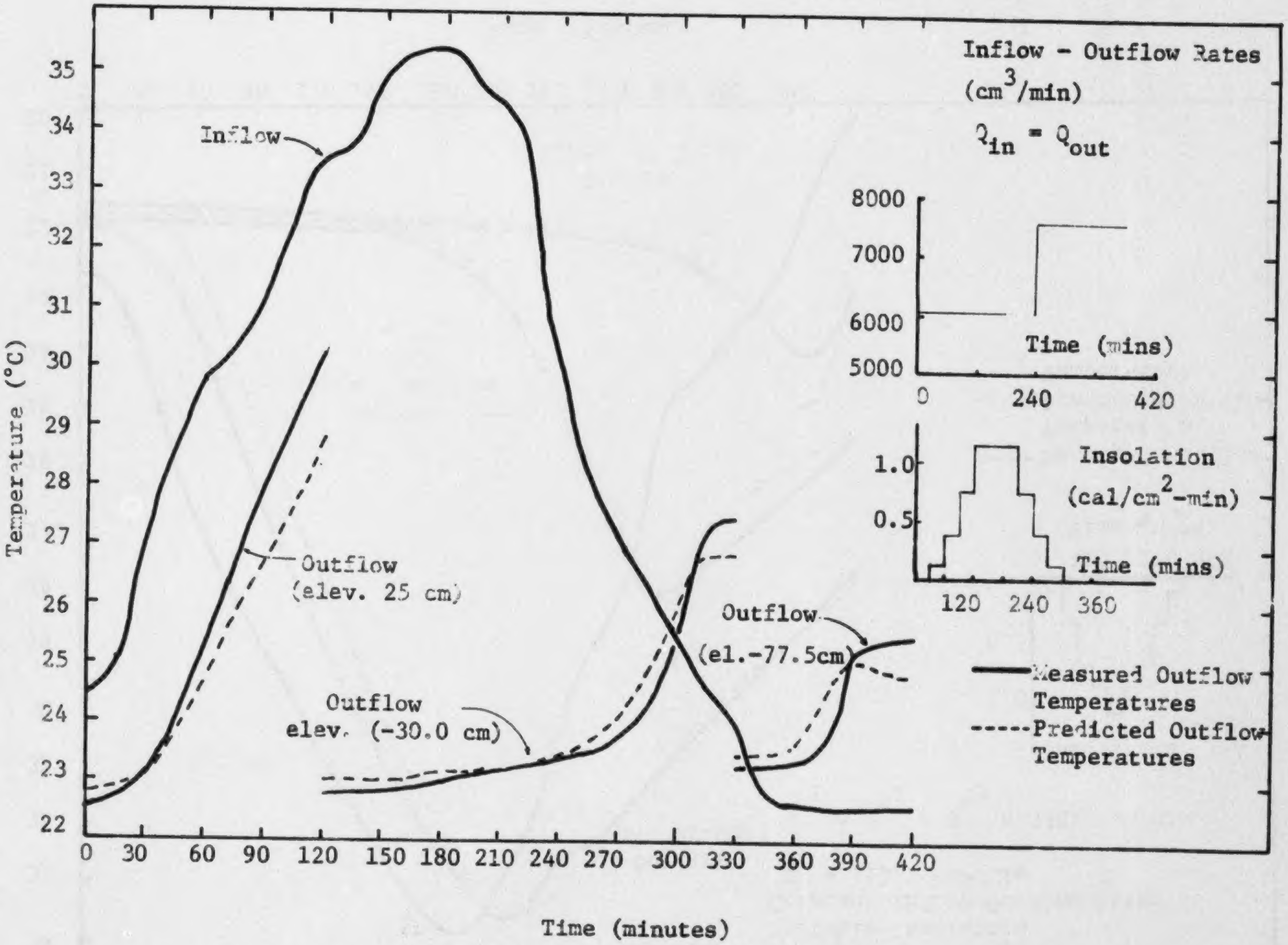


Figure 2.6 Outflow Temperatures. Alternate Withdrawal from Multiple Outlets

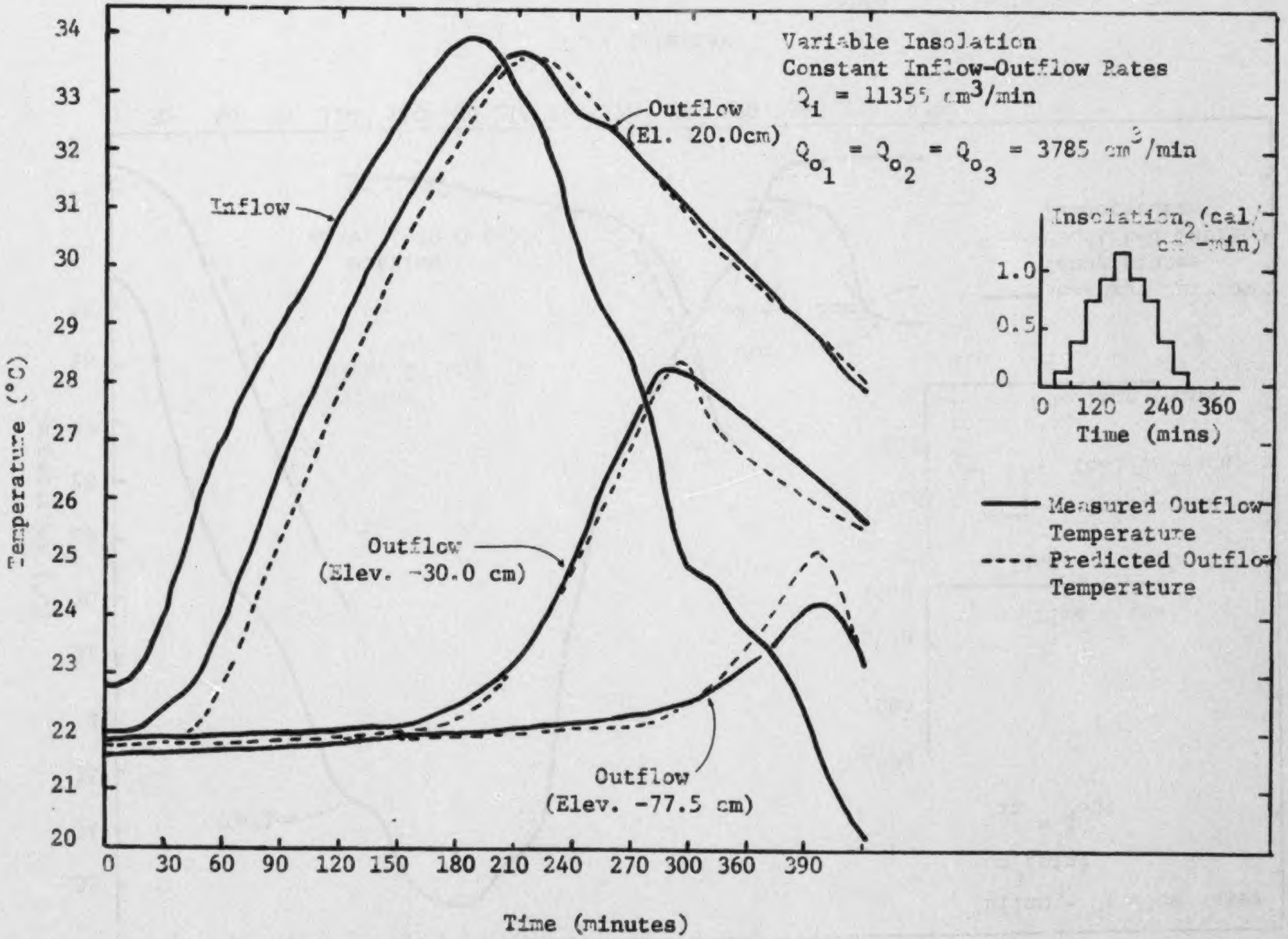


Figure 2.7 Outflow Temperatures. Simultaneous Withdrawal from Multiple Outlets

time its effect is observed in the measured temperature profile. This effect is enhanced by the fact that temperature profiles are usually taken near the outlet. This time lapse has been called the travel, or lag time, and is calculated as follows. The inflow entering on day N is calculated and labelled QQIN(N). The time lag is calculated by estimating the velocity of a uniform underflow, or density current, travelling down the upstream slope of the reservoir. The equations for the velocity and depth of the density current are given by

$$\bar{u} = \left(0.375 \left(\frac{g's}{\nu}\right)^{1/2} q\right)^{2/3} \tag{2.13}$$

and

$$d = 1.92 \left(\frac{q\,\nu}{g's}\right)^{1/3} \tag{2.14}$$

where

$g' = g\,\Delta\rho/\rho$

q = mixed inflow rate per unit width (see Section 2.3.10)

s = bottom slope of reservoir

ν = kinematic viscosity

d = thickness of density current

These formulae are obtained using Keulegan's (15) approach, under the assumption of laminar flow. The velocities and thicknesses predicted for Fontana were similar to those measured in the field by Elder and Wunderlich (8), and hence it seems reasonable to use these formulae for both the field and laboratory cases.

The density difference, $\Delta\rho$, and the travel distance are calculated as follows. The entering inflow QQIN(N), temperature TTIN(N) is allowed to mix with the surface waters. On the basis of the mixed temperature, the final position of the inflow in the water column is established. The downslope distance to this level, and the average density difference between the mixed inflow and the surrounding water are then easily established. Once the time lag LAGTIM(N) is known we have

QIN[N + LAGTIM(N)] = QQIN(N)

TIN[N + LAGTIM(N)] = TTIN(N)

i.e., an inflow entering the reservoir during time period N is not taken into account in the heat transport equations until time period [N + LAGTIM(N)]. The possibility of several days inflow affecting the temperature profiles at the same time is allowed for.

Alternatively, lag times were taken directly from laboratory observations of dye traces. A significant improvement in the predicted results followed, showing that discrepancies between predicted and measured occurrence times can be at least partly accounted for by this method. In the final analysis, however, it was decided that the improvement in results was more than offset by the non-predictive nature of the modifications. The facility has been kept in the model as part of the main program, but is usually bypassed.

2.3.9 Variable Surface Level

The surface level is calculated as a function of the initial surface level and the cumulative inflow and outflow. This was done to avoid the accumulation of roundoff errors. The continuous variation in the surface level is accounted for by allowing the thickness of the surface layer to vary between 0.25 Δy and 1.25 Δy where Δy is the layer thickness. The reason behind the lower limit on the thickness will become clearer when the overall schematization of the model, and the method of heat transport into the surface layer is discussed. Briefly, however, an extremely thin layer ($\sim\Delta y/100$) can lead to the calculation of very high surface temperatures, and unrealistic long wave radiation and evaporation losses. Within the range specified above, the model is not sensitive to the layer thickness.

In this model, there is no attempt to include the direct rainfall and evaporation into the calculation of surface level. This could be easily incorporated, if desired.

In the calculation of the surface level, an initial approximation is used, in that the surface element is considered to have vertical instead of sloping sides. A correction for the surface element thickness is later included to correct this approximation. The maximum correction observed was less than 1% of Δy. This procedure was used to simplify calculations, as the surface area, and hence the volume of the surface element is a function of the surface element thickness.

2.3.10 Entrance Mixing

When a river enters a reservoir it will entrain some of the reservoir water. The amount of this entrainment is one of the biggest unknowns in the present knowledge of reservoir behavior. It was found that changes in the amount of entrance mixing had a very significant effect on the computed temperature profiles and outflow temperatures. In fact it is possible to bracket the measured laboratory results with quite reasonable changes in the entrance mixing, as shown in Figures 2.9, 2.10, 2.11 and it therefore seems unreasonable to be concerned with heat transport due to eddy diffusion until more is known about the entrance mixing effect.

Direct measurements of entrainment in the laboratory reservoir gave the following results.

Inflow at surface (i.e. warm water)	50% entrainment
Inflow at intermediate depth	200% entrainment

Use of these values in the mathematical model for the laboratory case led to significant improvements in the correlation between predicted and measured results. See Figures 2.9 - 2.11.

Modification of the entrance to the laboratory flume reduced entrance mixing to between 10% and 50%, and this indicates that the geometry of the river entering the reservoir will probably be very significant.

No field measurements of entrance mixing were available, and hence the choice of an entrance mixing coefficient is somewhat arbitrary. Work in this laboratory on buoyant surface jets (28) indicates that an entrance mixing of 100% is realistic. This value gave excellent results (see Figure 2.12) but field studies should be undertaken.

Entrance mixing is simulated in the mathematical model by withdrawing a specified amount of water from a selected depth, d_m, and mixing this water with the inflow. The amount of water entrained per unit of inflow, is called the mixing ratio r. The mixed inflow rate Q'_{in} is therefore given by

$$Q'_{in} = (1 + r)\, Q_{in} \qquad (2.15)$$

where

Q_{in} = stream inflow rate.

For the Fontana case, with an entrance mixing of 100%, r is equal to unity, and the mixed inflow rate is twice the stream inflow rate.

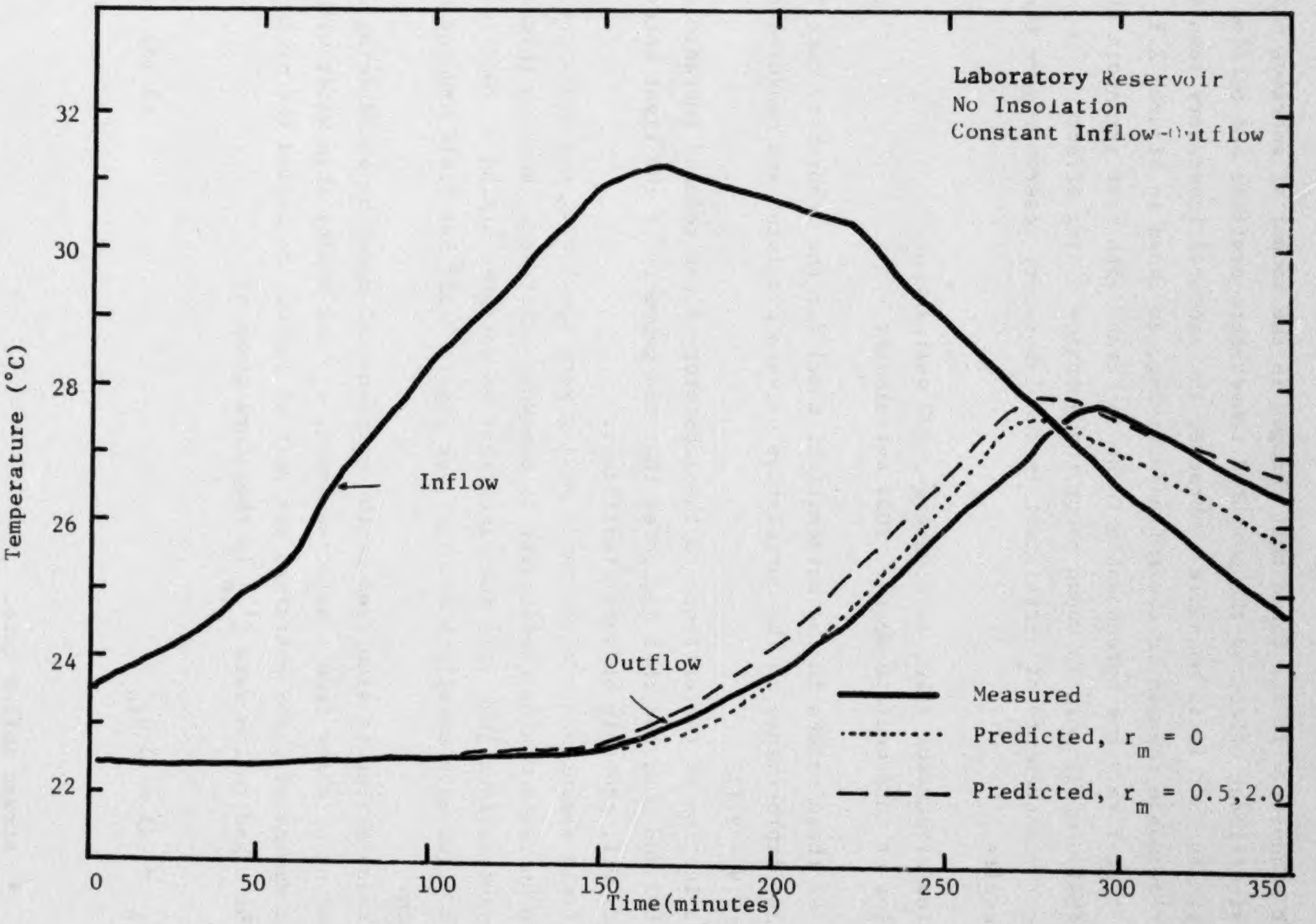


Figure 2.9 Effect of Entrance Mixing on Outflow Temperatures

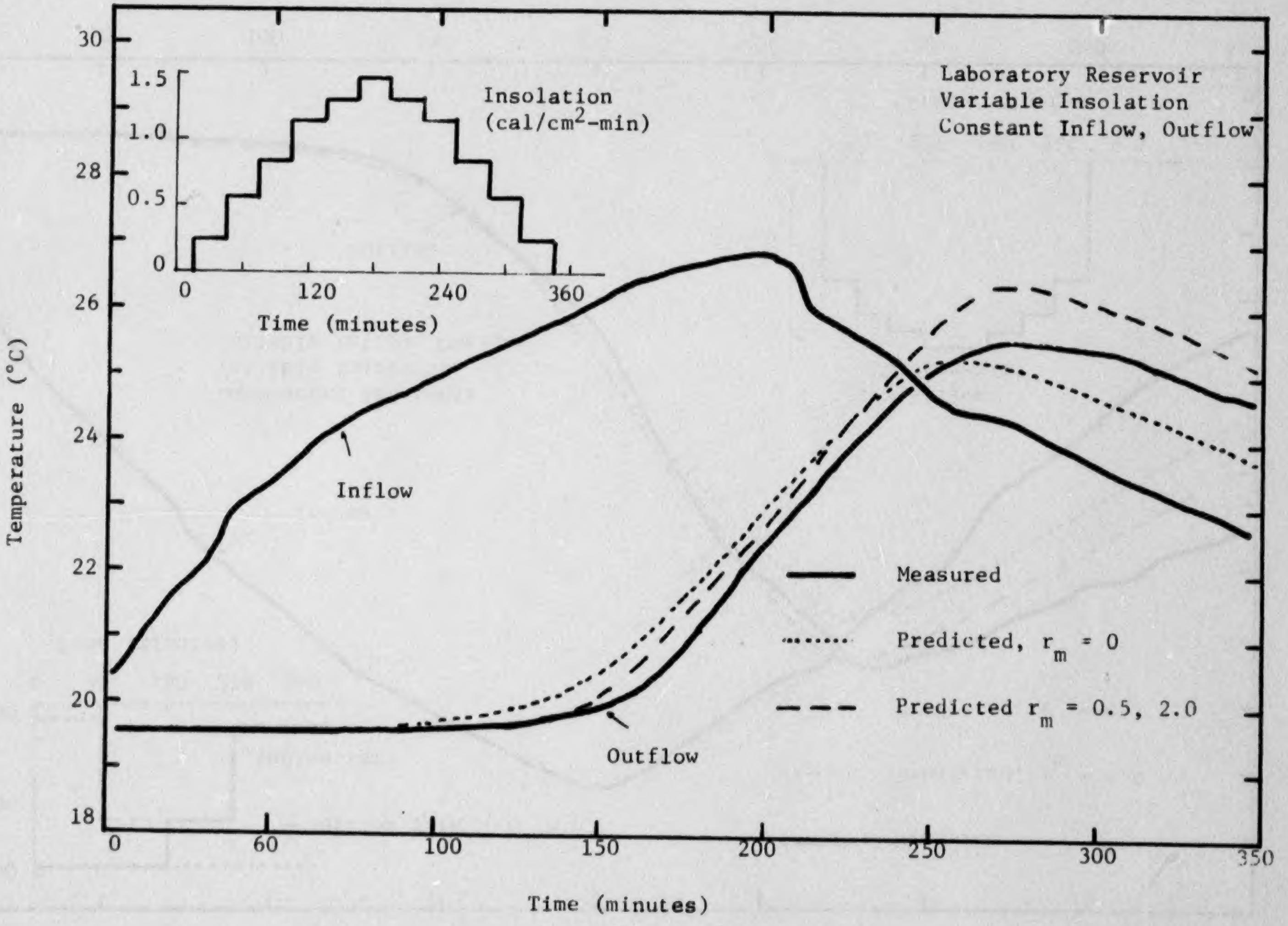


Figure 2.10 Effect of Entrance Mixing on Outflow Temperature

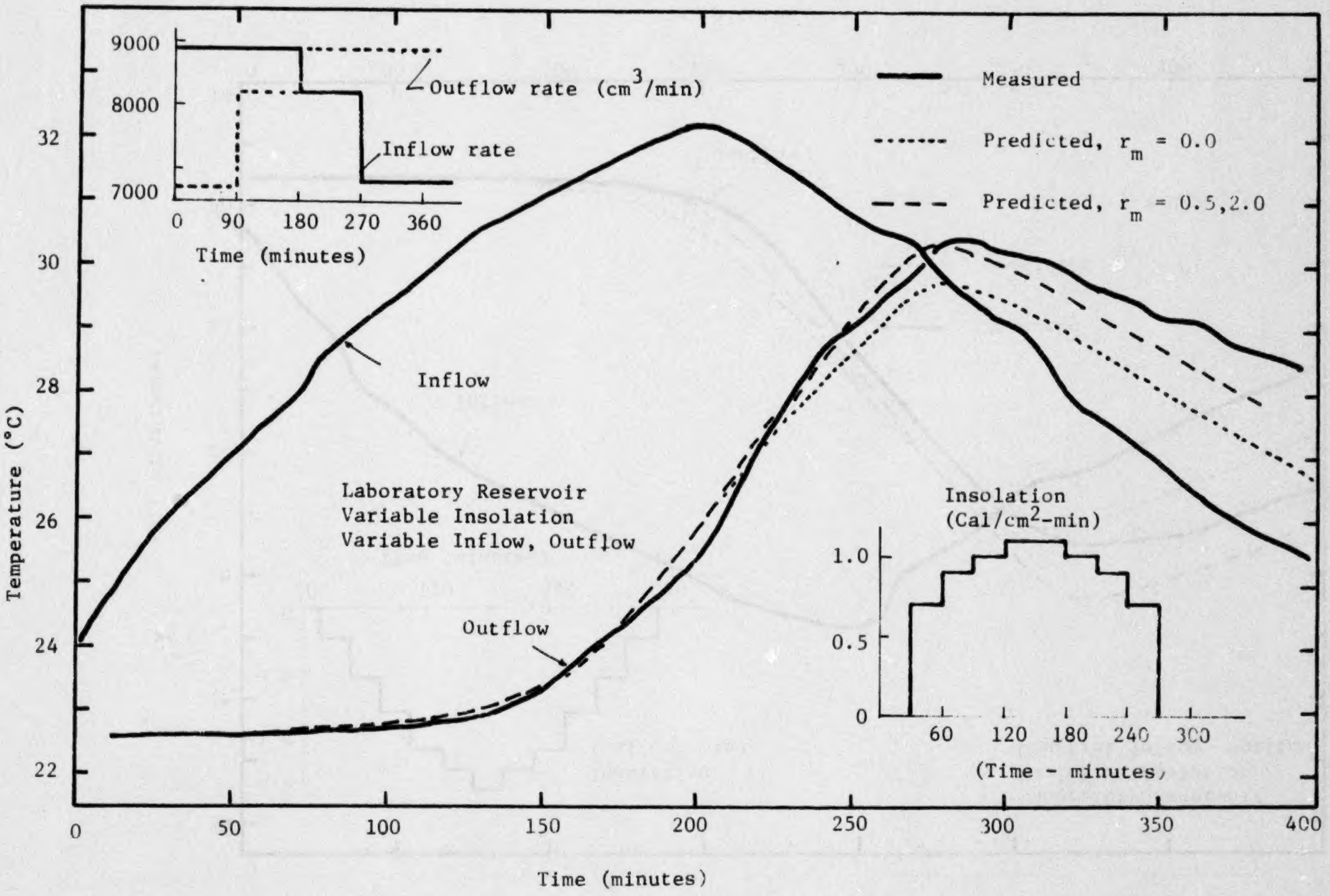


Figure 2.11 Effect of Entrance Mixing on Outflow Temperature

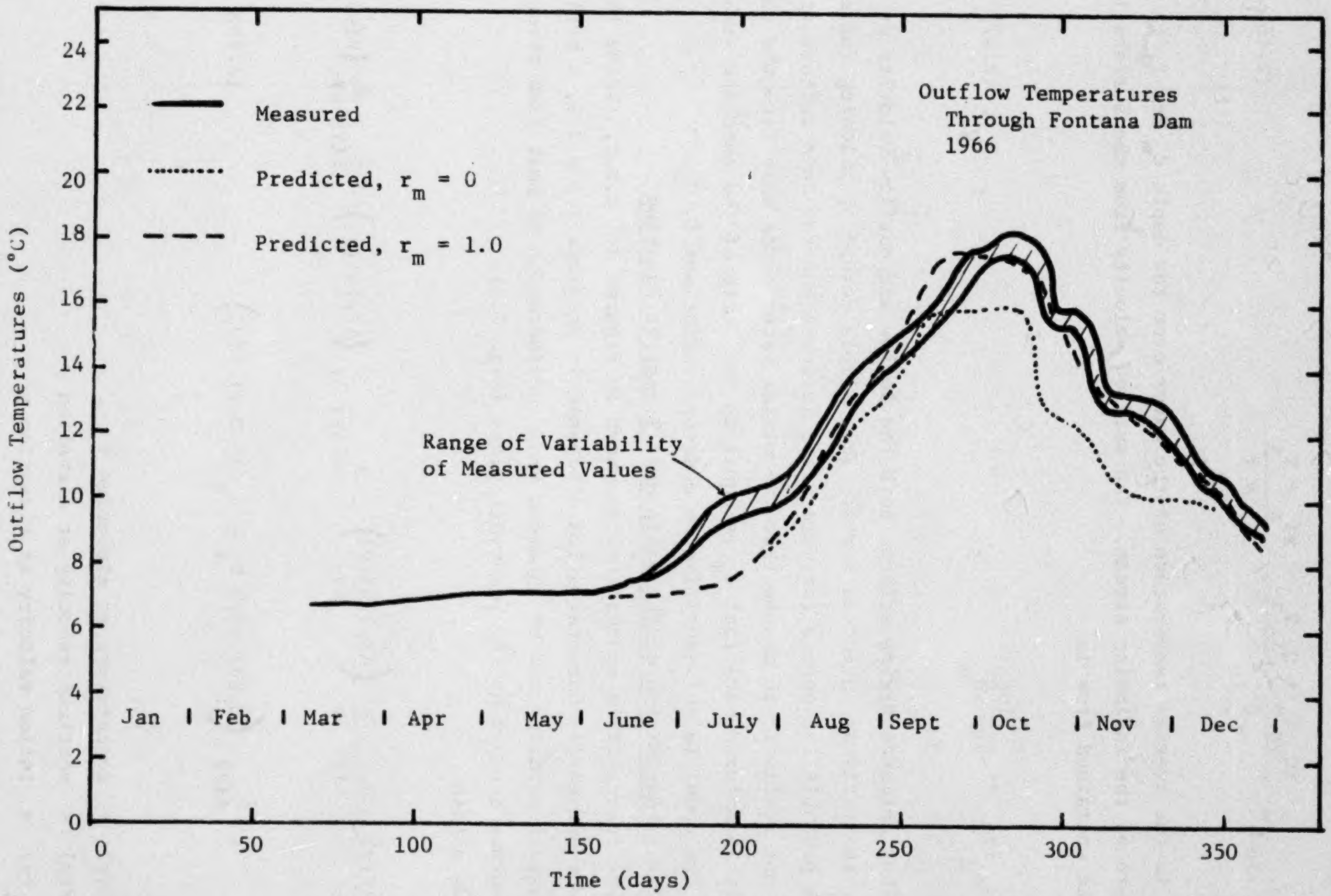


Figure 2-12. Effect of Entrance Mixing on Outflow Temperatures in Fontana Reservoir

The mixed inflow temperature T'_{in} is

$$T'_{in} = \frac{rQ_{in}T_m + Q_{in}T_i}{Q'_{in}} = \frac{rT_m + T_i}{1 + r} \qquad (2.16)$$

where T_m is the average temperature of the water over the depth d_m and T_i is the temperature of the inflowing stream. The outflow velocity from the surface layer due to the entrained flow is

$$u_{o_m}(y) = \frac{r\,Q_{in}}{B(y)\,d_m} \qquad (2.17)$$

Thus entrance mixing affects both the inflow and outflow velocity profiles and hence the vertical advection terms. This simple method of allowing for entrance mixing is probably reasonable for warm water inflows, but for cold inflows it is probably not realistic to assume that the mixing water comes only from the surface layer. It is assumed here that d_m is equal to the depth of the entering stream. However, the model is not sensitive to moderate variations in d_m.

2.4.1 Derivation of the Basic Heat Transport Equation

The reservoir is schematized as shown in Figures 2.1 a,b,c. Using the assumptions and model characteristics discussed in Sections 2.1 - 2.3, a basic heat transport equation can be obtained from consideration of heat flow through a control volume bounded by the reservoir sides (Fig. 2.2).

We obtain

$$\frac{\partial T(y)}{\partial t} = \frac{\alpha}{A(y)}\frac{\partial}{\partial y}\left(A(y)\frac{\partial T(y)}{\partial y}\right) - \frac{1}{\rho c A(y)}\frac{\partial}{\partial y}\left(A(y)\phi(y)\right) - \frac{1}{A(y)}\frac{\partial}{\partial y}\left(V(y)A(y)T(y)\right)$$

$$+ \frac{1}{A(y)}\left(u_i(y)\,B(y)\,T_i - u_o(y)\,B(y)\,T(y)\right) \qquad (2.18)$$

where

$T(y)$ = temperature at elevation y

$V(y)$ = vertical velocity at elevation y

$u_i(y)$ = inflow velocity at elevation y

$u_o(y)$ = outflow velocity at elevation y

T_i = inflow temperature

$A(y)$ = area at elevation (y)

t = time

α = molecular diffusivity

y = elevation (positive upwards)

2.4.2 Initial and Boundary Conditions

Equation 2.18 requires one initial and two boundary conditions. At the beginning of spring (t = 0), the reservoir is assumed to be in an isothermal state, and this provides the initial condition

$$T = T_o \text{ for all } y \text{ at } t = 0 \tag{2.19}$$

Conservation of heat at the water surface and the reservoir bottom give the two boundary conditions.

The detailed formulation of these boundary conditions is given in Sections 3.1.2 and 3.1.3.

3. Description of the Mathematical Model

3.0 Solution of the Heat Transport Equation

It was not possible to solve Equation 2.18 analytically, subject to the prescribed initial and boundary conditions, and thus a numerical solution was sought.

3.0.1 Choice of Numerical Scheme

Three basic finite difference methods are applicable to the convective-diffusion equation under consideration: (1) an explicit or forward difference scheme, (2) an implicit or backward difference scheme, (3) a combination of the first two which results in an implicit method also. In general, explicit schemes have the advantage in ease of formulation, and often in reduction in computer time. However, they are subject to certain stability requirements, which can restrict the size of the time step used in the solution. Implicit methods are unconditionally stable for any time step, but require more complicated methods of solution.

It will be shown, Section 3.0.3, that the limitations imposed by an explicit scheme are not unduly restrictive for the reservoir model. Furthermore, this type of scheme has the advantage of keeping separate the various terms in the heat transport equation, which facilitates alterations and corrections to the mathematical model.

It is recognized that the explicit scheme lacks the accuracy of a mixed scheme, such as that proposed by Stone and Brian (24) and used by Huber (12). This lack of accuracy, however, appears only in the treatment of the high frequency harmonics, and since the temperature profiles tend to be relatively smooth, these harmonics should not be too important. Furthermore, results of the explicit scheme have been compared with those from the Stone and Brian scheme, and the differences were insignificant.

3.0.2 Description of Numerical Scheme

The general mechanism of an explicit finite difference scheme is to find the value of a variable (e.g. temperature), as a function of space (e.g. depth), at a time step (n + 1), when the spatial distribution of the variable at time step (n) is known. The usual approach is to put previously derived differential equations such as Equation (2.18) in a finite difference form and to obtain approximate solutions for specific input data. Under some conditions, notably when large gradients exist, either in the dependent variable (e.g. temperature) or in coefficients (e.g. velocity), many finite difference formulations may lead to significant errors in heat or mass conservation. These errors may be avoided if the problem is formulated in terms of a control volume, such as in Figure 2.2. This approach is used here.

3.0.3 Limitations on Explicit Scheme

The use of an explicit finite difference scheme entails some limitations if numerical stability is to be maintained. The stability criteria for this case may be written

$$D \frac{\Delta T}{(\Delta y)^2} \leq \frac{1}{2} \tag{3.1}$$

$$V \frac{\Delta T}{\Delta y} < 1 \tag{3.2}$$

where

ΔT = time increment

Δy = distance increment

D = diffusion coefficient

V = magnitude of velocity in y direction

As long as turbulent diffusion is neglected, Equation (3.1) is not at all restrictive. However, Equation (3.2) can lead to a rather small Δt because of inflow conditions which usually occur only a small percentage of the time. This was remedied by use of a variable time step Δt. See Section 4.5.

3.1 Formulation of Explicit Finite Difference Scheme

This scheme is formulated by applying the heat balance approach to a typical reservoir control volume or element. The elements used were horizontal sections of the reservoir, bounded by the reservoir sides (see Figure 2.2). An internal element will be treated first, followed by surface and bottom elements.

3.1.1 Internal Element

The jth internal element for both the laboratory and field case is rectangular in plan, average length L_j, average width B_j, average area A_j and height Δy. In the field case the sides are considered to be insulated, i.e., $\frac{\partial T}{\partial n} = 0$ where n = normal to the side. In the laboratory case, however, heat losses through the sides are accounted for.

The rate of temperature change within the jth element (see Figure 3.1) is equal to the difference between the heat flow rate into and out from the element. The heat flow is made up of five terms, the direct absorption term, the diffusion term, the vertical advection term, the horizontal advection term, and the side loss term (laboratory case only).

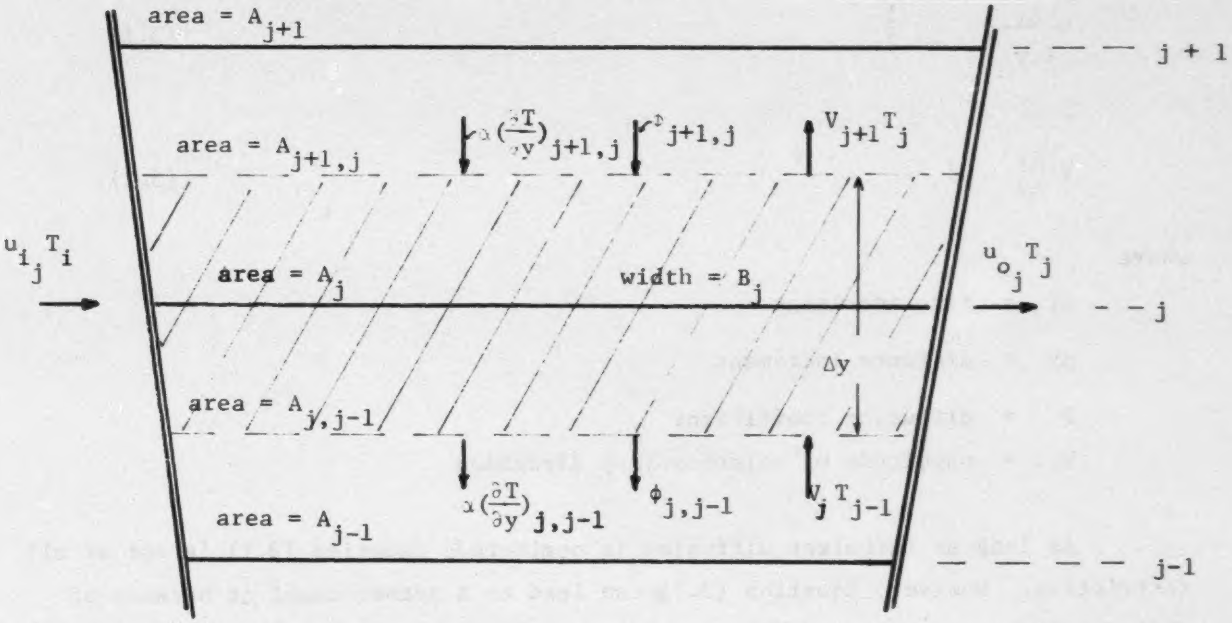

area = A_{j+1}
j + 1
area = A_{j+1,j}
α(∂T/∂y)_{j+1,j}
φ_{j+1,j}
V_{j+1} T_j
u_{i_j} T_i
area = A_j
width = B_j
u_{o_j} T_j
j
Δy
area = A_{j,j-1}
α(∂T/∂y)_{j,j-1}
φ_{j,j-1}
V_j T_{j-1}
area = A_{j-1}
j-1

Figure 3.1 Internal Element

3.1.1.1 Direct Absorption

The temperature change due to the direct absorption of transmitted radiation is given by

$$\Delta T_1 = \frac{1}{\rho c A_j \Delta y} \cdot \left(\phi_{j+1,j} A_{j+1,j} - \phi_{j,j-1} A_{j,j-1} \right) \cdot \Delta t \qquad (3.3)$$

The transmission of radiation has been discussed in Section 2.3.2.

3.1.1.2 Diffusion Term

$$\Delta T_2 = \frac{\alpha}{A_j \Delta y} \left(\frac{(T_{j+1} - T_j) \cdot}{\Delta y} A_{j+1,j} - \frac{(T_j - T_{j-1}) \cdot}{\Delta y} A_{j,j-1} \right) \cdot \Delta t \qquad (3.4)$$

α = molecular diffusion coefficient.

3.1.1.3 Vertical Advection Term

The vertical advection terms are of particular interest in this problem due to the configuration of the vertical velocity field. Depending on the elevation of the inflow, vertical velocities may be all positive (upwards), all negative, or positive at some elevations and negative at others. Thus the formulation of the vertical advection term is not straightforward. Four separate combinations of vertical velocities are possible and each combination requires a separate formulation, or serious errors result (Bella (3)).

Taking upwards as the positive direction and noting that V_j is defined at the bottom of the jth element we have

(a) $V_j, V_{j+1} > 0$

$$\Delta T_3 = \frac{1}{A_j \Delta y} \left(V_j T_{j-1} A_{j,j-1} - V_{j+1} T_j A_{j+1,j} \right) \cdot \Delta t \qquad (3.5)$$

(b) $V_j, V_{j+1} < 0$

$$\Delta T_3 = \frac{1}{A_j \Delta y} \left(V_j T_j A_{j,j-1} - V_{j+1} T_{j+1} A_{j+1,j} \right) \cdot \Delta t \qquad (3.6)$$

(c) $V_j > 0,\ V_{j+1} < 0$

$$\Delta T_3 = \frac{1}{A_j \Delta y} \left(V_j T_{j-1} A_{j,j-1} - V_{j+1} T_{j+1} A_{j+1,j} \right) \cdot \Delta t \qquad (3.7)$$

(d) $V_j < 0, V_{j+1} > 0$

$$\Delta T_3 = \frac{1}{A_j \Delta y} \left(V_j T_j A_{j,j-1} - V_{j+1} T_j A_{j+1,j} \right) . \Delta t \qquad (3.8)$$

3.1.1.4 Horizontal Advection Term

$$\Delta T_4 = \frac{1}{A_j \Delta y} \quad (u_{i_j} T_i - u_{o_j} T_j) \, . \, B_j \, \Delta y \quad . \Delta t \qquad (3.9)$$

3.1.1.5 Side Heat Loss Term - Laboratory Case Only

Huber and Harleman (12) assume that the outside wall of the plexiglas flume is at the same temperature as the inside and that radiation is the prime mechanism for heat loss. Both the reservoir sides and the laboratory surroundings are assumed to radiate almost as black bodies, leading to a net radiation loss rate for the sides of the jth element.

$$\phi_m = 0.97 \, k \left(T_j^{\,4} - T_a^{\,4} \right) \qquad (3.10)$$

where

T_a = room temperature

T_j, T_a are in °K

k = Stefan Boltzmann constant

This side heat loss term does not appear to have an important effect on the calculated temperature profiles, and Huber's treatment is deemed sufficient. The side heat loss term is

$$\Delta T_5 = -\frac{1}{\rho c A_j \Delta y} \quad [\phi_m (L_j + B_j) . 2\Delta y] . \Delta t \qquad (3.11)$$

$$\Delta T_5 = -\frac{1}{\rho c A_j} \quad [2\phi_m (L_j + B_j)] \quad . \Delta t \qquad (3.12)$$

3.1.1.6 Total Temperature Change

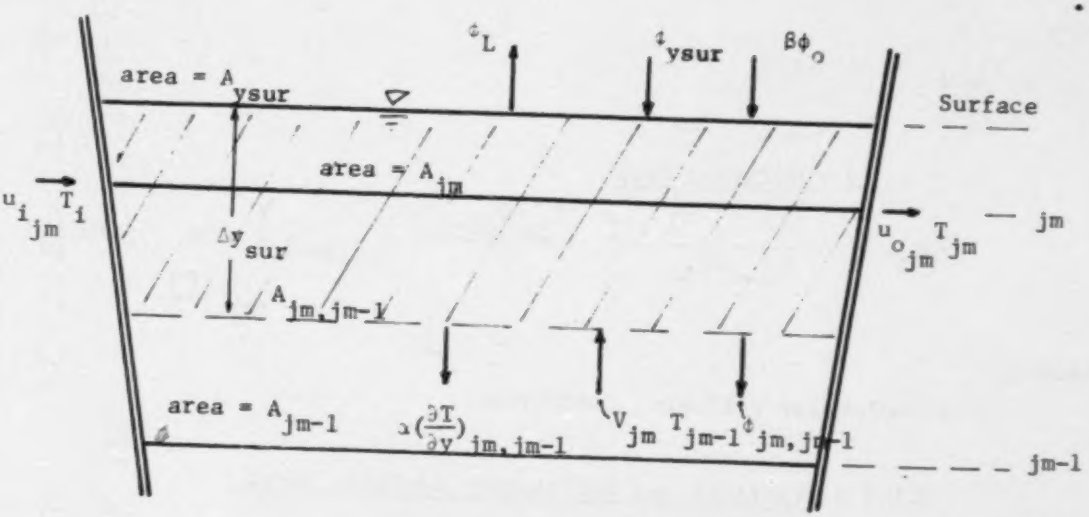
For the case of the field reservoir the total temperature change ΔT_f, in time increment Δt, is given by

$$\Delta T_f = \Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 \tag{3.13}$$

For the special case of the laboratory reservoir the extra side heat loss term must be added to the above Equation (3.13).

3.1.2 Surface Element

The surface boundary condition is obtained in a similar manner to the equation for the internal element, namely, by writing a heat balance equation for a specified control volume. In this case, however, the thickness of the control volume varies, and extra heat sources and sinks have to be considered. (See Figure 3.2)



ϕ_L
ϕ_{ysur}
$\beta\phi_o$
area = A_{ysur}
Surface
area = A_{jm}
$u_{i_{jm}}$ T_i
Δy_{sur}
$u_{o_{jm}}$ T_{jm}
jm
$A_{jm,jm-1}$
area = A_{jm-1}
$\alpha(\frac{\partial T}{\partial y})_{jm,jm-1}$
V_{jm} T_{jm-1}
$\phi_{jm,jm-1}$
jm-1

Figure 3.2 Surface Element

The new surface level is calculated before any heat flow is considered. Once Δy_{sur} is known, velocities are calculated such that

$$u_{i_{jm}} B_{jm} \Delta y_{sur} + V_{jm} A_{jm,jm-1} = u_{o_{jm}} B_{jm} \Delta y_{sur} \tag{3.14}$$

An average surface area, S_{area}, is also calculated such that

$$S_{area} = (A_{ysur} + A_{jm,jm-1})/2 \tag{3.15}$$

3.1.2.1 Direct Absorption Term

$$\Delta T_1 = \frac{1}{\rho c S_{area} \Delta y_{sur}} \left(\phi_{ysur} A_{ysur} - \phi_{jm,jm-1} A_{jm,jm-1} \right) . \Delta t \tag{3.16}$$

where

$$\phi_{ysur} = (1-\beta)\, \phi_o \tag{3.17}$$

3.1.2.2 Diffusion Term

$$\Delta T_2 = - \frac{\alpha}{S_{area} \Delta y_{sur}} \left(\frac{(T_{jm} - T_{jm-1}).}{\Delta y} A_{jm,jm-1} \right) . \Delta t \tag{3.18}$$

where

α = molecular diffusion coefficient.

3.1.2.3 Vertical and Horizontal Advection Terms

$V_{jm} > 0$

$$\Delta T_{3,4} = \frac{1}{S_{area} \Delta y_{sur}} \Big(V_{jm} T_{jm-1} A_{jm,jm-1} + u_{i_{jm}} B_{jm} \Delta y_{sur} T_i$$

$$- u_{o_{jm}} B_{jm} \Delta y_{sur} T_{jm} \Big) . \Delta t \tag{3.19}$$

Substituting from Equation (3.14)

$$\Delta T_{3,4} = \frac{1}{S_{area}\Delta y_{sur}} \left(V_{jm} A_{jm,jm-1} (T_{jm-1} - T_{jm}) + u_{i_{jm}} B_{jm} \Delta y_{sur} (T_i - T_{jm}) \right) \cdot \Delta t \qquad (3.20)$$

$V_{jm} < 0$

$$\Delta T_{3,4} = \frac{1}{S_{area}\Delta y_{sur}} \left(V_{jm} A_{jm,jm-1} T_{jm} + u_{i_{jm}} B_{jm} T_i \Delta y_{sur} \right.$$

$$\left. - u_{o_{jm}} B_{jm} T_{jm} \Delta y_{sur} \right) \cdot \Delta t \qquad (3.21)$$

Substituting from Equation (3.14) the V_{jm} term disappears and

$$\Delta T_{3,4} = \frac{1}{S_{area}} \left(u_{i_{jm}} B_{jm} (T_i - T_{jm}) \right) \cdot \Delta t \qquad (3.22)$$

3.1.2.4 Side Loss Term - Laboratory Reservoir Only

This term is independent of layer thickness, and is therefore given by Equation (3.12)

3.1.2.5 Surface Absorbed Solar Radiation Term

In Section 2.3.2 it was pointed out that a fraction, β, of the solar radiation can be considered to be absorbed at the surface

$$\Delta T_6 = \frac{1}{\rho c S_{area} \Delta y_{sur}} \left(\beta \phi_o A_{ysur} \right) \cdot \Delta t \qquad (3.23)$$

3.1.2.6 Surface Heat Loss Term

All heat losses from the field reservoir, apart from advective losses, take place from the reservoir surface. The total heat loss rate per unit area, ϕ_L, can be written as

$$\phi_L = \phi_e + \phi_c + \phi_{ra} \qquad (3.24)$$

where

ϕ_e = rate of heat loss due to evaporation

ϕ_c = rate of heat loss due to conduction

ϕ_{ra} = rate of heat loss due to net longwave radiation

See Chapter 4 for further discussion of these parameters.

The surface heat loss term is given by

$$\Delta T_7 = -\frac{1}{\rho c S_{area} \Delta y_{sur}} \left(\phi_L A_{ysur} \right) \cdot \Delta t \qquad (3.25)$$

3.1.2.7 Total Temperature Change

For the case of the field reservoir, the total temperature change in the surface element ΔT_s, in time increment Δt, is given by

$$\Delta T_s = (\Delta T_1 + \Delta T_2 + \Delta T_{3,4} + \Delta T_6 + \Delta T_7)_{j=jm} \qquad (3.26)$$

For the laboratory case the side loss term $(\Delta T_5)_{j=jm}$ must also be included.

3.1.3 Bottom Element

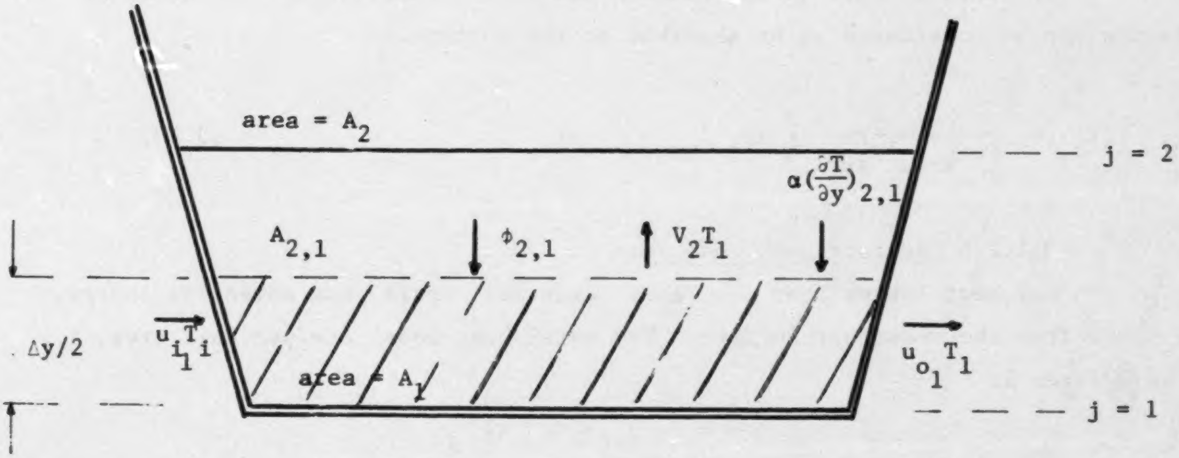

area = A_2
j = 2
$\alpha(\frac{\partial T}{\partial y})_{2,1}$
$A_{2,1}$
$\phi_{2,1}$
$V_2 T_1$
$\Delta y/2$
$u_{i_1} T_i$
area = A_1
$u_{o_1} T_1$
j = 1

Figure 3.3 Bottom Element

The bottom element differs from the internal elements in two ways. Firstly, it is half as thick, so that the point j = 1 coincides with the bottom. Secondly, there is no heat flow through the lower interface. The average area is defined as

$$A_b = (A_{2,1} + A_1)/2 \tag{3.27}$$

3.1.3.1 Direct Absorption Term

$$\Delta T_1 = \frac{1}{\rho c A_b \Delta y/2} \left(\phi_{2,1} \cdot A_{2,1} \right) . \Delta t \tag{3.28}$$

3.1.3.2 Diffusion Term

$$\Delta T_2 = \frac{1}{A_b \frac{\Delta y}{2}} \left(\alpha \frac{T_2 - T_1}{\Delta y} \cdot A_{2,1} \right) . \Delta t \tag{3.29}$$

3.1.3.3 Vertical and Horizontal Advection Terms

$V_2 > 0$

$$\Delta T_{3,4} = \frac{1}{A_b \frac{\Delta y}{2}} \left(u_{i_1} T_i B_1 \frac{\Delta y}{2} - V_2 T_1 A_{2,1} - u_{o_1} T_1 B_1 \frac{\Delta y}{2} \right) . \Delta t \tag{3.30}$$

But V_2 is defined by

$$V_2 A_{2,1} = B_1 \frac{\Delta y}{2} \left(u_{i_1} - u_{o_1} \right) \tag{3.31}$$

$$\Delta T_{3,4} = \frac{1}{A_b \frac{\Delta y}{2}} \cdot u_{i_1} B_1 \frac{\Delta y}{2} \left(T_i - T_1 \right) . \Delta t \tag{3.32}$$

For $V_2 < 0$

$$\Delta T_{3,4} = \frac{1}{A_b \Delta y/2} \left(u_{i_1} B_1 \frac{\Delta y}{2} \left(T_i - T_1\right) - V_2 A_{2,1} \left(T_2 - T_1\right) \right) . \Delta t \qquad (3.33)$$

3.1.3.4 Side Loss Term

$$\Delta T_5 = \frac{-1}{\rho c A_b} \left[2\phi_m \left(L_1 + B_1\right)\right] . \Delta t \qquad (3.34)$$

3.1.3.5 Total Temperature Change

For the case of the field reservoir the total temperature change for the bottom element ΔT_b, in time increment Δt, is given by

$$\Delta T_b = \left(\Delta T_1 + \Delta T_2 + \Delta T_{3,4}\right)_{j=1} \qquad (3.35)$$

For the laboratory reservoir, the side loss term $(\Delta T_5)_{j=1}$ must be included.

3.2 Convective Mixing

As discussed in Section 2.3.3 convective mixing is allowed to take place whenever the temperature gradient $\frac{\partial T}{\partial y}$ is negative. Under most conditions this instability should occur only in the surface layer, where the heat loss due to evaporation and back radiation often exceeds the heat input due to surface absorbed radiation. However, in shallow or very clear reservoirs, some solar radiation reaches the bottom, where it is absorbed. This leads to a warm bottom layer, which then mixes with the colder water above it. It is thought that only instabilities with a physical origin will occur, but it is possible that under some conditions of inflow and outflow small numerical instabilities may appear, although these have not been observed. For this reason the whole profile is examined for instabilities, and these are eliminated by mixing.

The mixing is controlled by a simple energy balance equation, e.g.,

$$\int_{y_{mix}}^{y_s} \left(T(y) - T_m\right) . A(y) . dy = 0 \qquad (3.36)$$

where y_{mix} = the elevation of the bottom of the mixed layer

$T_m = T_m(t)$ = mixed temperature at time t

This procedure is carried out in subroutine AVER. The surface layer is examined. If the temperature is lower than that of the next layer, the top two layers are mixed. The mixed temperature is compared with that of the third layer, and if necessary, the top three layers are mixed. This process continues until a stable profile is obtained.

3.3 Energy Check

Since the surface losses are a function of the surface temperature, it is possible for large errors to occur in the overall energy balance without this being evident from the calculated profiles, since any error tending to increase or decrease the surface temperature, causes an increase or decrease, respectively, in the heat loss from the surface, and thus a compensating effect is introduced. For this reason a check is made on the energy balance for each time period. The most sensitive check is the ratio between the increase in stored energy and the net energy inflow. However, when the net energy inflow approaches zero, this ratio can be misleading, and for this reason, a second ratio is given, which compares the total energy stored plus the energy outflow, with the initial energy plus the energy inflow.

3.4 Numerical Dispersion

One of the drawbacks of numerical schemes involving advection terms, is that inaccuracies tend to be introduced. These take the form of an additional diffusion or dispersion effect, and are called numerical dispersion. A detailed treatment of this effect is given by Bella (3). For the one-dimensional variable area case, the numerical dispersion coefficient can be written as

$$D_{n_j} = \frac{V_j}{2}\left(\Delta y - V_j \frac{A_j}{A_{j,j-1}} \cdot \Delta t\right) \qquad (3.37)$$

where

A_j = horizontal cross section area at center of jth element

$A_{j,j-1}$ = horizontal cross section area at interface between jth and (j-1)th element, see Figure 3.1.

For most reservoir cases the one-dimensional constant area form is sufficient i.e.

$$D_{n_j} = \frac{V_j}{2} (\Delta y - V_j \Delta t) \tag{3.38}$$

By differentiating Equation (3.38) with respect to V, it can be shown that $D_{n_{max}}$ occurs for $V = \Delta y/2\Delta t$. The maximum numerical dispersion is therfore given by

$$D_{n_{max}} = \frac{(\Delta y)^2}{8\Delta t} \tag{3.39}$$

For the field case $\Delta t = 1$ day, $\Delta y = 2$ meters, this results in $D_{n_{max}}$ equal to 40 times the molecular diffusion coefficient, which is still a relatively small value. For the laboratory case, $\Delta y = 2$ cm, $\Delta t = 1$ minute, this results in $D_{n_{max}}$ equal to ~7 times the molecular value.

Since this model uses a very small diffusion coefficient, it is not possible to minimize the effect of numerical dispersion by replacing α with $(\alpha - D_n)$ in the diffusion term. However, it seems reasonable to use the opposite procedure, namely replacing α by $(\alpha + D_n)$, thus doubling the numerical dispersion, to see if this error has a significant effect. From Figure 3.4 it can be seen that the effect of doubling the error is a minor one, and hence it seems likely that numerical dispersion is not significant in this case.

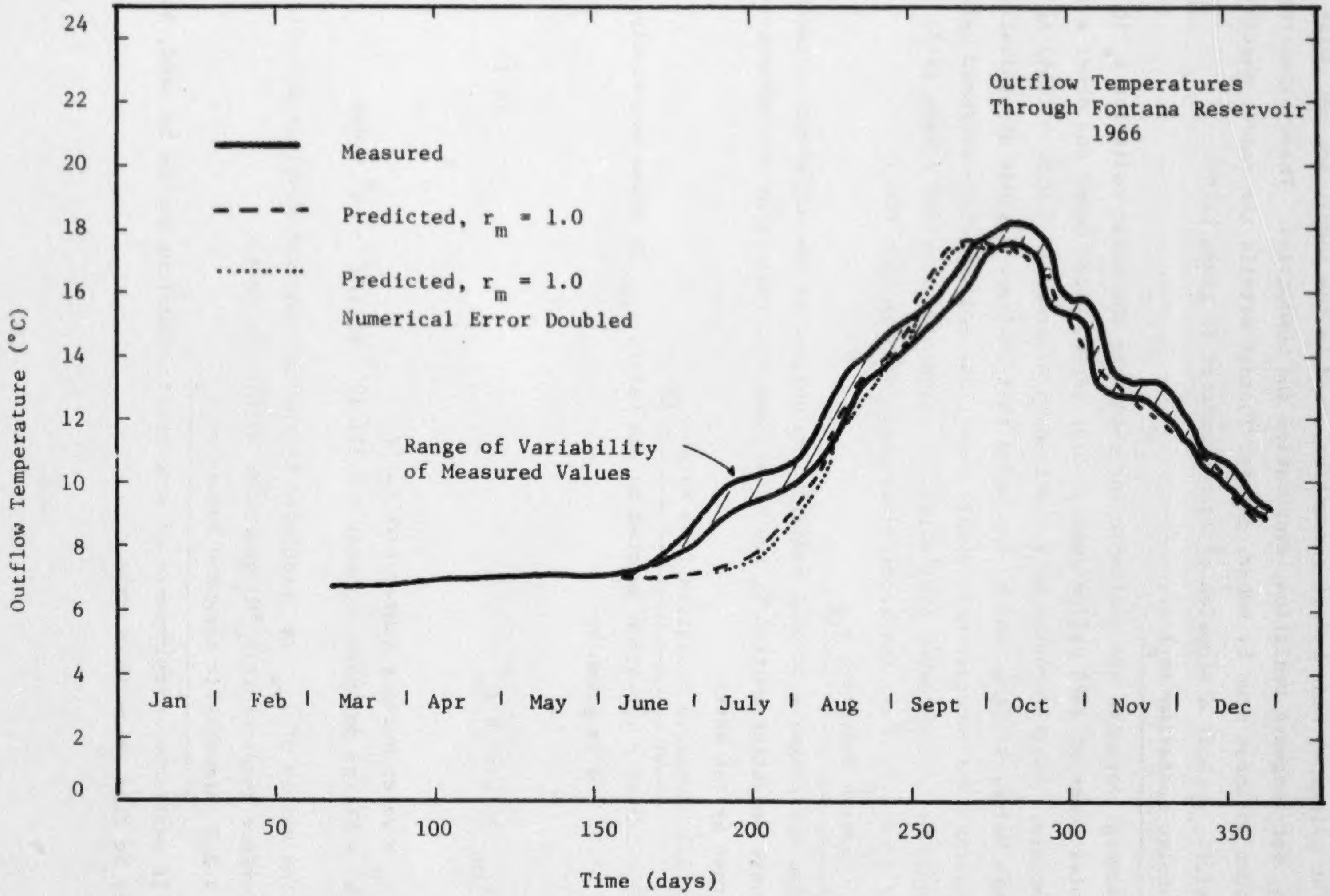


Figure 3.4 Effect of Numerical Dispersion on Outflow Temperatures

4. Determination of Parameters

The principal heat budget parameters, used in the model, are net solar radiation, net longwave radiation, evaporation and conduction. These parameters are the same as those used by Huber, and for further details the reader should consult (12). A short discussion of each parameter is given below.

4.1 Net Solar Radiation (ϕ_o)

Several formulae are available for obtaining the solar radiation ϕ_s in terms of the solar constant (1·98 cal/cm^2/min), solar angle, cloud cover and other atmospheric factors. These formulae were examined by Andersen (U.S.G.S. - 1954) as part of the Lake Hefner studies, and he concluded that indirect methods of evaluating solar radiation are accurate only within about 15%, and therefore measured values of ϕ_s should be used whenever available. A reasonable value for albedo is 7% (1). Values of $\phi_o = \phi_s(1 - a_r)$ are required as input data in this model.

4.2 Net Longwave Radiation ϕ_{ra}

The net longwave or back radiation is defined as the difference between the longwave radiation emitted by the water, and that emitted by the atmosphere, and absorbed by the water.

4.2.1 Longwave Radiation from Water ϕ_{rw}

The longwave radiation emitted by the water, ϕ_{rw}, is known accurately (within ± 1/2% (1)), and is given by

$$\phi_{rw} = 0.97\, k\, T_w^{\,4} \tag{4.1}$$

where T_w = water surface temperature in °K
k = Stefan Bolzmann constant = $1.171\ 10^{-6}$ kcal/m^2 - °K^4 - day

The values of ϕ_{rw} are calculated by the mathematical model as a function of the surface temperature(T_w°K) generated within the model.

4.2.2 Atmospheric Longwave Radiation ϕ_a

If available, measurements of atmospheric radiation should be used, and values of ϕ_a may be read in as input data.

If measurements are not available, reasonable values of ϕ_a may be calculated as a function of air temperature and cloud cover. The best approach appears to be that of Wunderlich, who uses Swinbank's (27) clear sky formula, modified for cloudiness.

$$\phi_a = 0.937 \cdot 10^{-5}\, k\, T_a^{\,6}\, (1.0 + 0.17\, c^2) \qquad (4.2)$$

where

c = fraction of sky covered by clouds

T_a = air temperature °K, 2 meters above the water surface.

Thus for the field case, assuming 3% reflection of ϕ_a by the water surface

$$\phi_{ra} = 0.97k\, [T_w^{\,4} - 0.937\, T_a^{\,6}\, (1.0 + 0.17\, c^2)] \qquad (4.3)$$

The option of calculating the net longwave back radiation ϕ_{ra} as a function of air temperature, water temperature and cloud cover is included in the model.

For the laboratory case, the room containing the model is assumed to radiate as a grey body at air temperature. Thus we have

$$\phi_{ra} = 0.97k\, (T_w^{\,4} - T_a^{\,4}) \qquad (4.4)$$

This calculation is incorporated in the model.

4.3 Evaporation and Conduction Losses

Field evaporation and conduction losses are difficult to predict, or for that matter to measure. Most formulae are based on Dalton's law of mass transfer, modified to allow for the effect of wind. A general form is

$$E_m = \rho (a + b\, W)\, (e_s - \psi e_a) \qquad (4.5)$$

where

E_m = mass flux

a,b = empirical constants

W = wind speed

e_s = saturation vapor pressure at the temperature of the water surface

e_a = saturation vapor pressure of the air at temperature T_a

ψ = relative humidity

The heat loss is given by

$$\phi_e = E_m (L_v + cT_s) \tag{4.6}$$

where L_v = latent heat of vaporization

$= 595.9 - 0.54\, T_s$ (4.7)

T_s = surface temperature in °C

Conduction losses are usually related to the mass flux (E_m) by the Bowen ratio R where

$$R = N \frac{(T_s - T_a)}{(e_s - \psi e_a)} \tag{4.8}$$

where N = constant

Thus,

$$\phi_e + \phi_c = \rho(a + bW)\,(e_s - \psi e_a)\left(L_v + cT_s + N\frac{(T_s - T_a)}{(e_s - \psi e_a)}\right) \tag{4.9}$$

Note - T_a is in °C

4.3.1 Field Evaporation

The model contains the option of using the Rohwer (21) or the Kohler (17) formula, both of which are based on Equation 4.9. In the field case used to verify the model (Fontana Reservoir) best results were obtained with the Rohwer formula, and thus this formula is recommended.

4.3.1.1 Rohwer Formula

The value of $(\phi_e + \phi_c)$ is in kcal/m^2 - day and the units are as follows:

ρ in kg/m^3,

a = 0.000308 m/day-mm Hg,

b = 0.000185 sec/day-mm Hg,

W in m/sec (measured six inches above the surface),

e_s in mm Hg,

e_a in mm Hg,

ψ is expressed as a fraction,

L_v in kcal/kg,

c in kcal/kg-°C,

N = 269.1 kcal-mm Hg/kg-°C

No specification of the elevation for the measurement of T_a is given. Rohwer's formula can thus be expressed in the form of Equation 4.9 as

$$\phi_e + \phi_c = \overset{\underline{\text{Rohwer - Field}}}{(0.000308 + 0.000185W)}\, \rho(e_s - \psi e_a) \left(L + cT_s + \frac{269.1(T_s - T_a)}{(e_s - \psi e_a)} \right) \quad (4.10)$$

4.3.1.2 Kohler Formula

This field evaporation formula is due to Kohler (1954) as given by Wunderlich. The quantity $\phi_e + \phi_c$ will have units of kcal/m^2 -day where

ρ in kg/m^3,

a = 0,

b = 0.000135 sec/day-mb,

W in m/sec (not less than 0.05 m/sec),

W is measured two meters above the surface,

e_s and e_a in mb (milli-bars),

ψ is expressed as a fraction,

L_v in kcal/kg,

c in kcal/kg-°C

N = 372 kcal-mb/kg-°C

T_a is measured two meters above the surface.

The Kohler formula is expressed in the form of Equation 4.9 as

$$\phi_e + \phi_c = \overset{\underline{\text{Kohler - Field}}}{0.000135W\rho(e_s - \psi e_a)} \left(L_v + cT_s + \frac{372(T_s - T_a)}{(e_s - \psi e_a)} \right) \quad (4.11)$$

where all quantities have the units cited.

4.3.2 Laboratory Evaporation

For laboratory conditions, the wind dependent term can be neglected, and the value of the constant (a) was found to depend on the mode of surface heating. Values of (a) were obtained from laboratory measurements and applied in Rohwer's formula.

4.3.3 Negative Evaporation

In some cases the vapor pressure gradient given by the term $(e_s - \psi e_a)$ is negative which leads to a negative evaporation loss. While it is known that this phenomenon occurs in nature, in the formation of dew, nevertheless little is known about the process when it occurs over a water surface, and the constants in Equations 4.10, 4.11, apply only in the case of a positive vapor pressure gradient. For this reason, when the evaporation is found to be negative, it is put equal to zero. The conduction term is kept, however, although since it was initially obtained as a function of evaporation, the accuracy of the formula used is open to question.

4.4 Required Input Data

For best results the following parameters should be measured in the field:

1. Solar radiation
2. Atmospheric radiation
3. Air temperatures
4. Relative humidities
5. Wind speeds
6. Streamflow rate
7. Streamflow temperature

If necessary, solar radiation and atmospheric radiation can be calculated, and in this case the cloud cover should be known. Inflow rates and temperatures can be obtained from streamflow records. The extinction coefficient of the water (η) can be obtained either from Secchi disk, or underwater photometer readings taken in the lake, reservoir, (or river, if the reservoir is not yet built). However some change in η may be expected when the reservoir is built. It should be noted that the required input data is such that it would be available if a reservoir were planned.

4.5 Selection of Time and Distance Steps

An important step in the use of the model is the choice of the distance increment Δy, and the time step Δt. Both Δy and Δt are restricted by the two stability criteria

$$D \frac{\Delta t}{(\Delta y)^2} \leq \frac{1}{2} \tag{4.12}$$

and

$$V \frac{\Delta t}{\Delta y} \leq 1 \tag{4.13}$$

where

D = diffusion coefficient

V = vertical velocity

Other factors such as the input data, and depth of reservoir may also be important. A reasonable approach would be to choose Δy first, based on the depth of the reservoir. A minimum of twenty (20) increments is recommended. Approximately fifty (50) increments have been used in the model verification runs. Too small a Δy leads to very costly runs and the possibility of instabilities near the surface. See Section 4.5.4. Once Δy is chosen, Δt_{max} may be obtained from the stability criteria. A value of V_{max} for use in Equation (4.13) may be taken as

$$V_{max} = \frac{Q_{out}}{A_{out}} \tag{4.14}$$

where

Q_{out} = outlet discharge

A_{out} = horizontal area of reservoir at outlet

Once Δt_{max} is known, a reasonable value of Δt, based on the input data, may be chosen. For a field reservoir, a Δt of one day is a reasonable choice.

4.5.1 Variable Time Step

Under certain inflow conditions, in particular high inflow rates and low inflow temperatures, V_{max} may be considerably larger than that given by Equation (4.14) and thus the stability criterion (4.13) may be violated. These inflow conditions may exist for a very small percentage of the annual cycle, and it is unrealistic to base the choice of Δt on them. This is remedied by reducing Δt during the critical period. For each time period the vertical velocity profile is scanned and the maximum velocity (in either direction) is selected. The criterion (4.13) is now considered and if violated, a new Δt is selected such that the smallest integer number of new Δt's is equal to the previous time interval. In the cases considered the extra time involved was insignificant, but in some reservoirs with a high inflow/capacity ratio this could lead to very expensive runs. However, a basic assumption of the model, namely that isotherms are planar and horizontal, restricts the model to reservoirs with a low inflow/capacity ratio.

4.5.2 Lower Limit on Δy in Field Reservoir

It has been found that if the surface layer is much less than 0.5 meters, oscillations may occur in the surface temperature under some conditions. This is due to the fact that when there is a net positive heat flux into a thin surface layer, large temperature increases result. This is followed in the next time step by unrealistically large surface heat losses, which lower the surface temperature, thus increasing the likelihood of a large positive heat flux in the next time step. Large oscillations in the surface temperature may result. The usual case of a net negative heat flux into the surface layer is not affected by the layer thickness as mixing with the lower layers occurs, and the layer thickness is accounted for here. To eliminate these oscillations, a lower limit of 0.5 meters is applied to the surface layer thickness.

4.6 Possible Program Changes

Apart from the redefining of the minimum surface layer thickness to allow for a smaller Δy, other changes may be found necessary when the program is applied to different field cases.

4.6.1 Cut-Off Gradient

As discussed in Section 2.3.6.2, to avoid the withdrawal of warm surface waters when this would be physically unrealistic, the width of the withdrawal layer is limited by means of a cut-off gradient. The choice of the limiting gradient is somewhat arbitrary, and if unrealistic outflow temperatures are obtained, this value may have to be changed.

4.6.2 Entrance Mixing

The present method of allowing for dilution of the streamflow as it enters the reservoir is considered unsatisfactory, and should be changed as soon as information about this process becomes available.

5. Criteria for Applicability of Model

The assumption of horizontal isotherms is basic to the mathematical model developed in this study. The following criteria may be used to determine whether this assumption is valid.

5.1 Wind Mixing Criterion for Lakes and Reservoirs

Shallow lakes and reservoirs in exposed conditions tend to have tilted isotherms during periods of high wind velocity. Since this effect is only a temporary one, it can probably be neglected, except in the case where the thermocline reaches the surface. In this case, the hypolimnion is mixed with the epilimnion by direct wind action, and Mortimer (18) considers that it is this mechanism which accounts for the increases in depth of the epilimnion after a windy spell. The inclination of the thermocline (here defined as the bottom of the surface mixed layer) can be obtained as follows.

Sverdrup (25) gives the inclination (i_s) of the surface due to wind effects as

$$i_s = 4 \times 10^{-7} \cdot \frac{W^2}{h} \tag{5.1}$$

where

h = average depth of water (m)

W = wind speed (m/sec) (use mean of the maximum wind speed)

The inclination of the thermocline i_t is given by

$$i_t = i_s \frac{\rho}{\Delta\rho} \tag{5.2}$$

The maximum displacement d_t of the thermocline by the wind is therefore

$$d_t = i_t \cdot \frac{L_t}{2}$$

where

L_t = average length of lake in the thermocline region, in the direction of the wind (m).

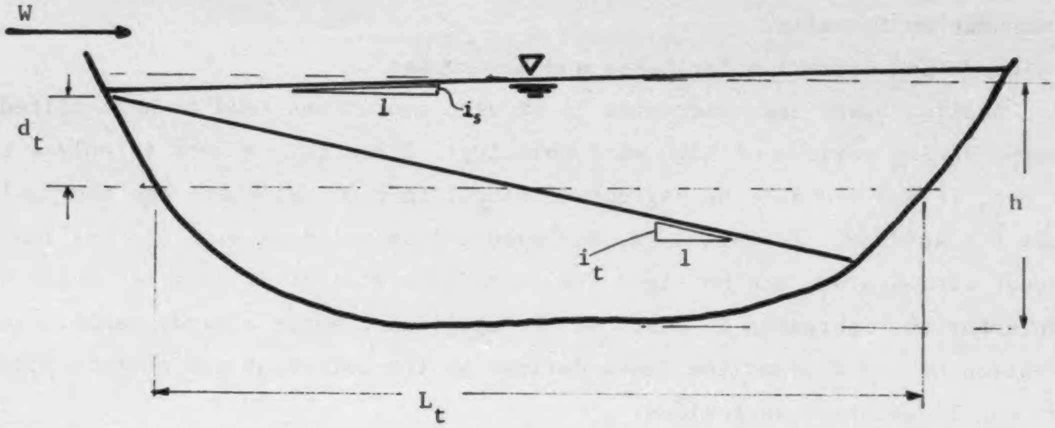


Figure 5.1 Effect of Wind on Thermocline

The criterion for use of the model is that the mixed depth (h_m), calculated in the model for midsummer, should be greater than the thermocline displacement (d_t) for mean maximum wind conditions, i.e.,

$$h_m > \frac{4.10^{-7} W^2}{h} \cdot \frac{\rho}{\Delta\rho} \cdot \frac{L_t}{2} \tag{5.3}$$

$\Delta\rho$ = density difference between epilimnion and hypolimnion

If the inequality (5.3) is satisfied, the mathematical model is applicable in the case of a lake. For a reservoir, however, the following criterion must also be satisfied.

5.2 Flow Through Criterion for Reservoirs

When the flow through the reservoir is large in comparison to the reservoir capacity, the best criterion is that of Orlob (20), who introduces a densimetric Froude number which is a function of the flowthrough rate, the reservoir geometry and a density difference. The criterion is

$$\mathbb{F}_D = \frac{LQ}{h\mathbb{V}} \sqrt{\frac{1}{g\varepsilon}} < \frac{1}{\pi} \tag{5.4}$$

where

ε = average normalized density gradient in reservoir and is taken by Orlob to be 10^{-3} m^{-1}

L = length of reservoir (m)

h = mean reservoir depth (m)

$\mathbb{V}$ = reservoir volume (m^3)

Q = flow through rate m^3 sec^{-1}

This leads to

$$\mathbb{F}_D = 320 \frac{L}{h} \frac{Q}{\mathbb{V}} \tag{5.5}$$

For Fontana $\mathbb{F}_D \simeq \frac{1}{100}$. Other strongly stratified reservoirs e.g. Hungry Horse and Detroit reservoirs show similar results.

Lake Roosevelt ($F_D \sim \frac{1}{2}$) exhibits weak stratification only.

The above criteria tend to limit the model to the deeper reservoir, with a low discharge/capacity ratio. However, a large percentage of the reservoirs fall into the above category, and this is particularly true for those reservoirs for which water quality predictions are required.

6. Verification of Mathematical Model for Field Reservoirs

The mathematical model was verified for the field case using data from Fontana Reservoir. During 1966 the TVA Engineering Laboratory at Norris, Tennessee, conducted an extensive field study of the reservoir in which all pertinent hydrological and meteorological parameters were measured. These data are among the best presently available with which to compare predicted and measured temperature distributions for the field reservoir situation.

6.1 Description of Reservoir

Fontana Reservoir, shown in Figure 7.1, is located on the Little Tennessee River in western North Carolina. It is approximately twenty-nine (29) miles long and is fed by three rives, the Little Tennessee, the Tuckasegee, and Nantahala rivers as well as many smaller streams. The reservoir is highly stratified during the summer.

6.2 Input Data

All data used in the program are listed in Section 7.9 in the form of computer input. Certain data were available on an hourly basis and other data on a daily basis. The program was run with time steps of one day and all hourly data were reduced to daily averages.

Air temperatures, relative humidities and wind speeds were available on an hourly basis. The latter were measured at a reservoir shore location and transformed to mid-lake values by an empirical correlation provided by the TVA Engineering Laboratory.

Inflow data was available on a daily basis for the three tributaries listed above and for runoff from the watersheds bordering the north and south shorelines. The sum of these sources is used as the reservoir inflow, and the inflow temperature was taken as the weighted average of the inflow temperatures from each of the five sources. The outflow rate and temperature were available on a daily basis.

The solar radiation values were computed by Huber (12) and correlated for a limited number of cases with measured values obtained by TVA. There is some doubt as to the accuracy of these values. See Huber (12) for details. Values of atmospheric radiation were computed by Equation 4.2 for each hour and averaged on a daily basis.

Geometric data, namely areas and lengths of the reservoir were available at fifty foot intervals. These values are used as input data, and values at intermediate elevations are found by linear interpolation.

The values of the absorption coefficient, η, and surface absorption fraction, β, were obtained from photometer measurements in Fontana Reservoir (29).

6.3 Results

The comparison of predicted versus measured values for outflow temperature as a function of time is given in Figure 6.2. Predicted versus measured temperature profiles are given in Figures 6.3 - 6.6.

The measured temperature data was taken during the 1966 study (29).

The agreement between predicted and measured values for both outflow temperature and temperature profiles is very good. As noted previously, the effect of entrance mixing is significant, at least towards the end of the yearly cycle.

6.4 Verification from Other Sources

A modified version of this model has been checked against data from Lake Norman in North Carolina with good results (23). The modifications were necessary because of a thermal power station which uses Lake Norman as a source of cooling water.

A simplified version of the model has been checked against data from Lake Tahoe, and Castle Lake, California, and from Manton Reservoir in Northern Australia (22). Good agreement was obtained in all cases, but the quality of the available meteorological and hydrological data was much lower than for Fontana Reservoir, and these results are not presented here.

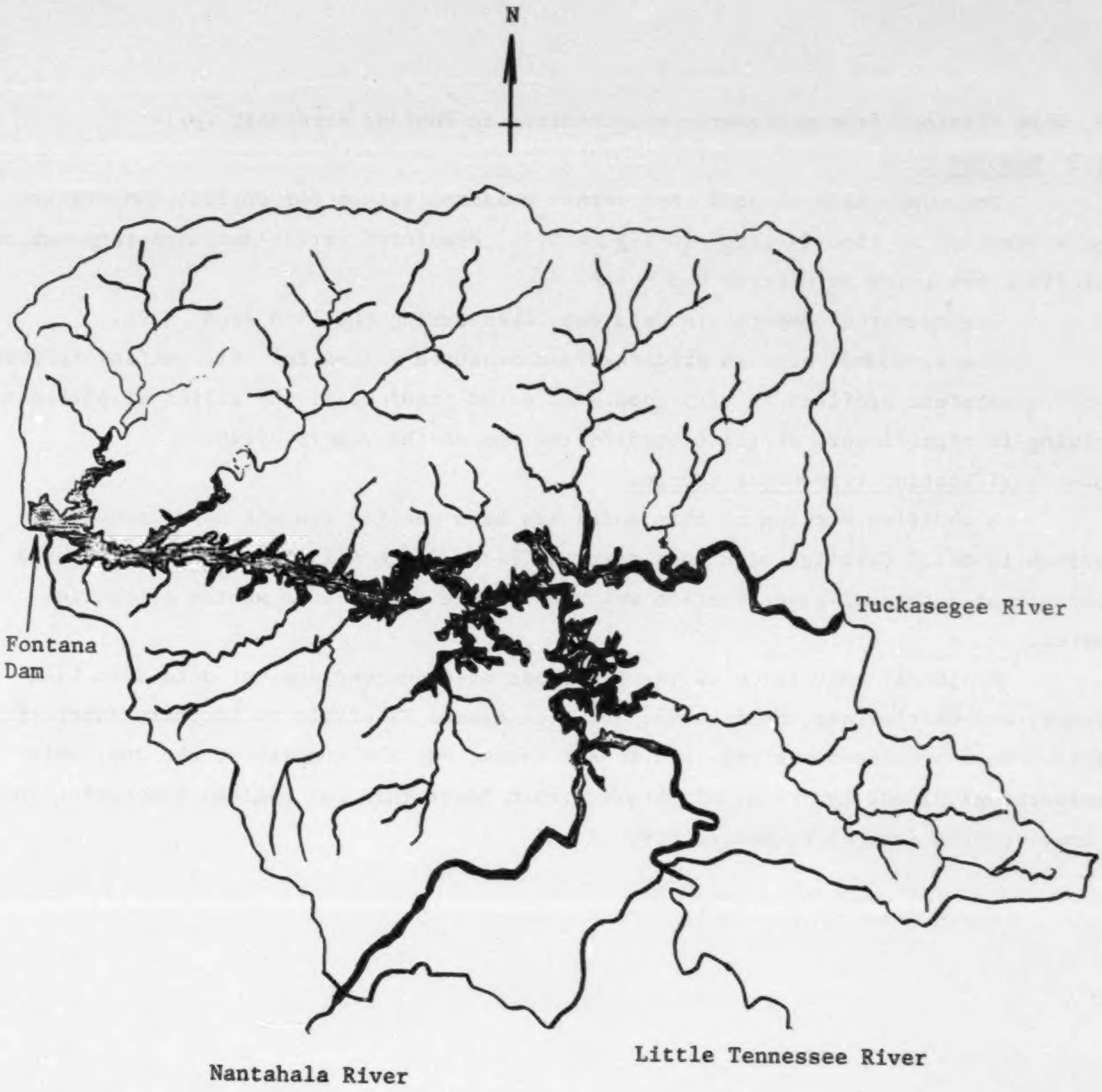

N
Tuckasegee River
Fontana Dam
Little Tennessee River
Nantahala River

Figure 6.1 Map of Fontana Reservoir and Watershed

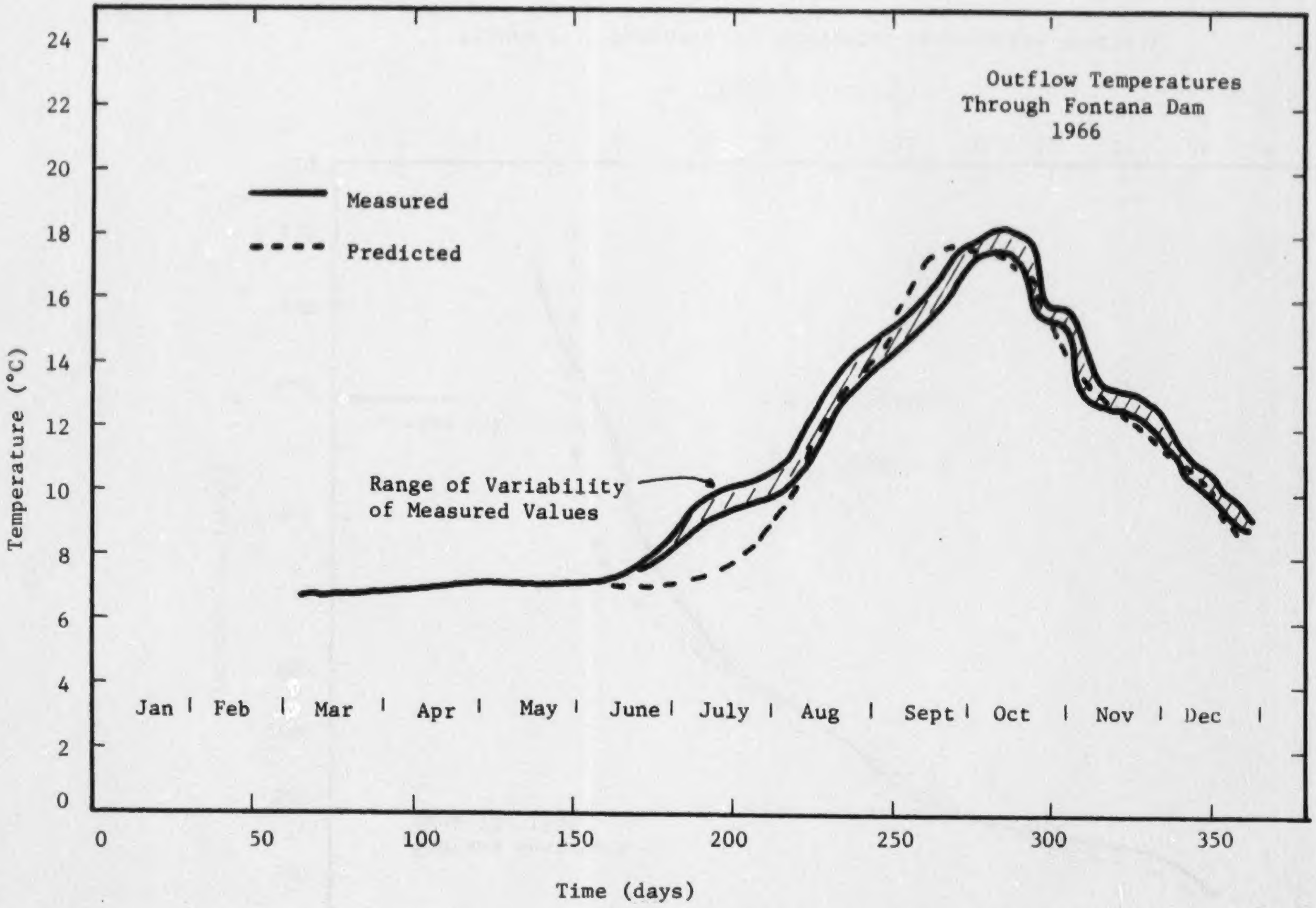


Figure 6.2 Measured and Predicted Outflow Temperatures Through Fontana Dam

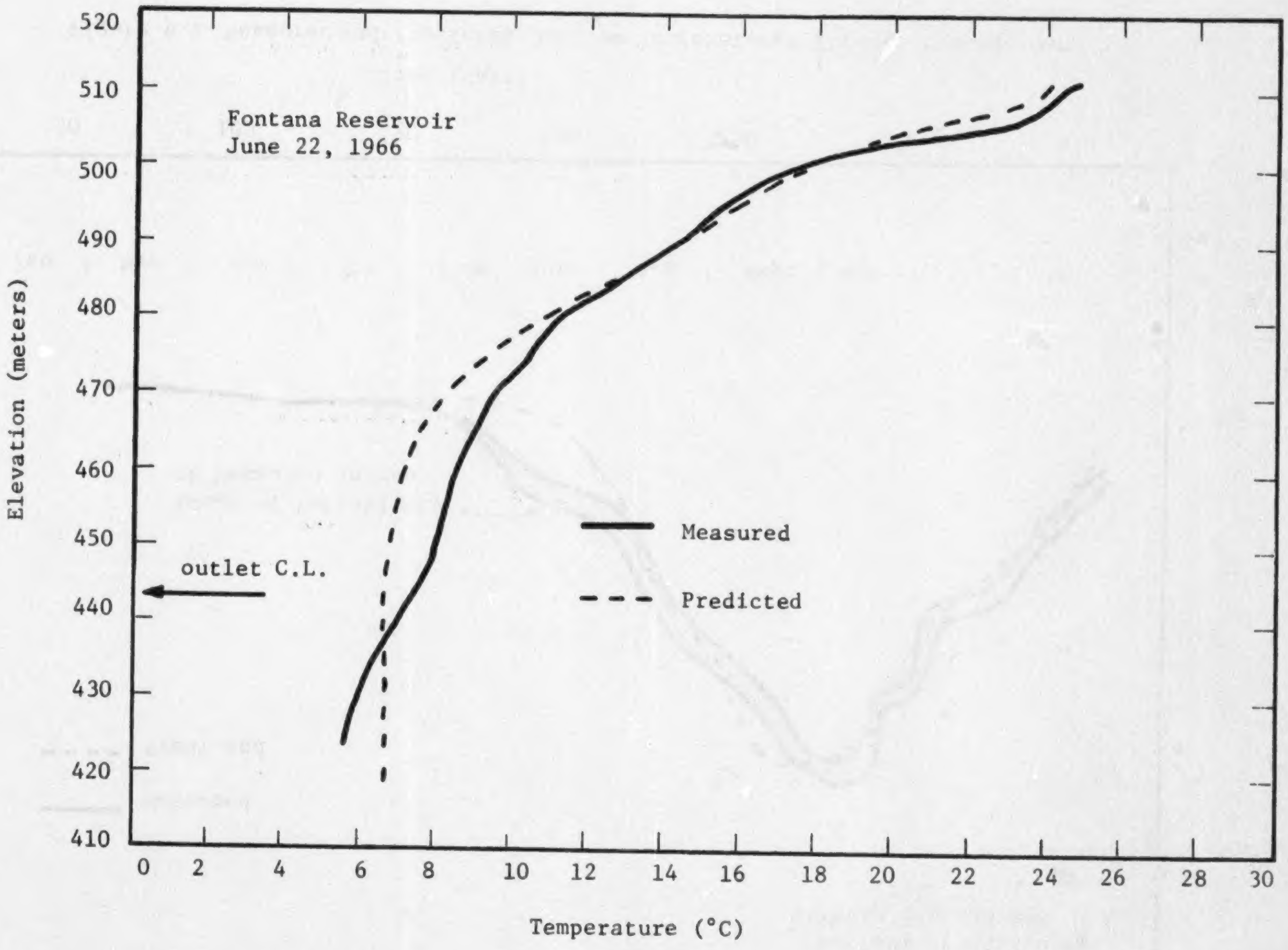


Figure 6.3 Measured and Predicted Temperature Profiles

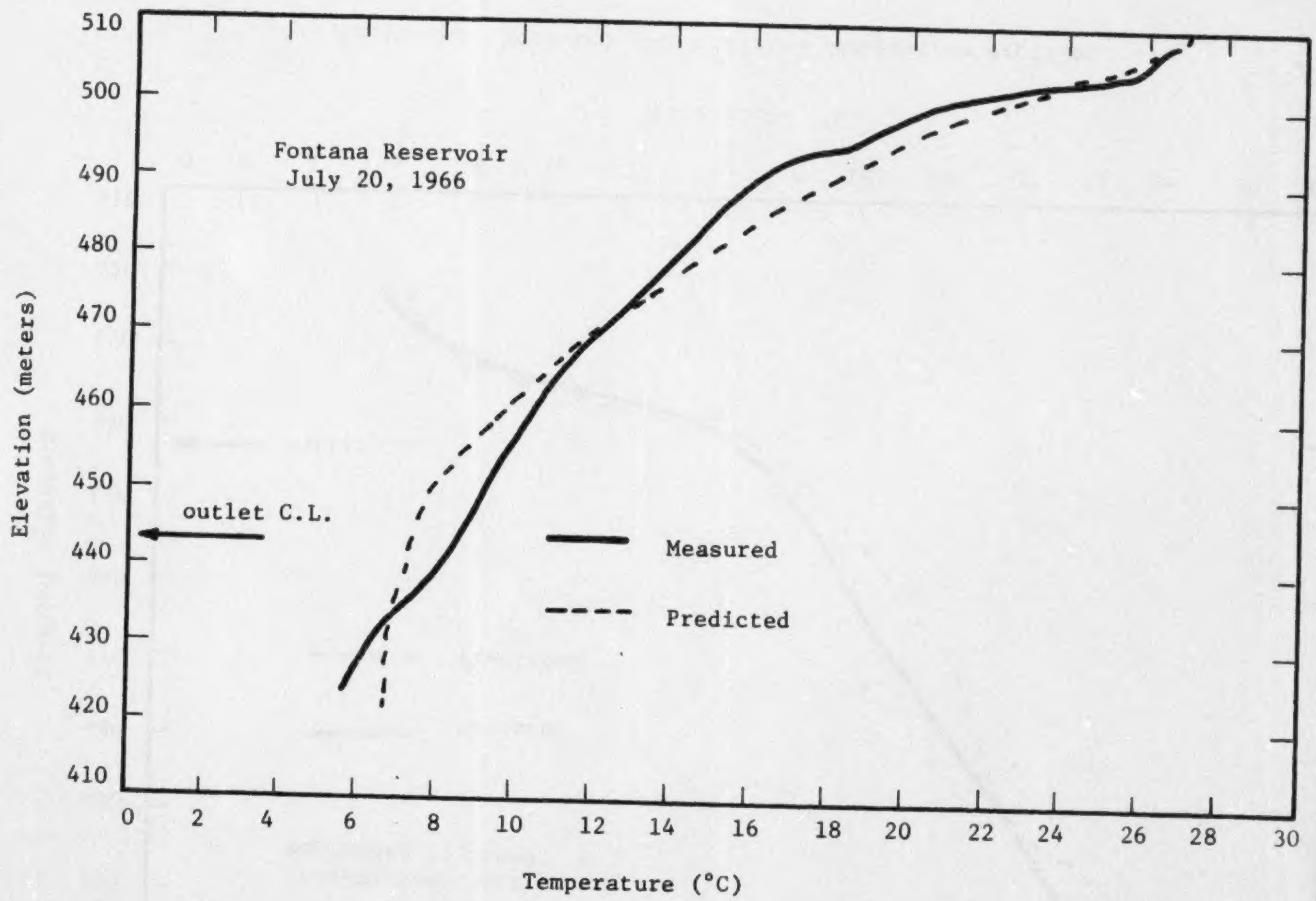


Figure 6.4 Measured and Predicted Temperature Profiles

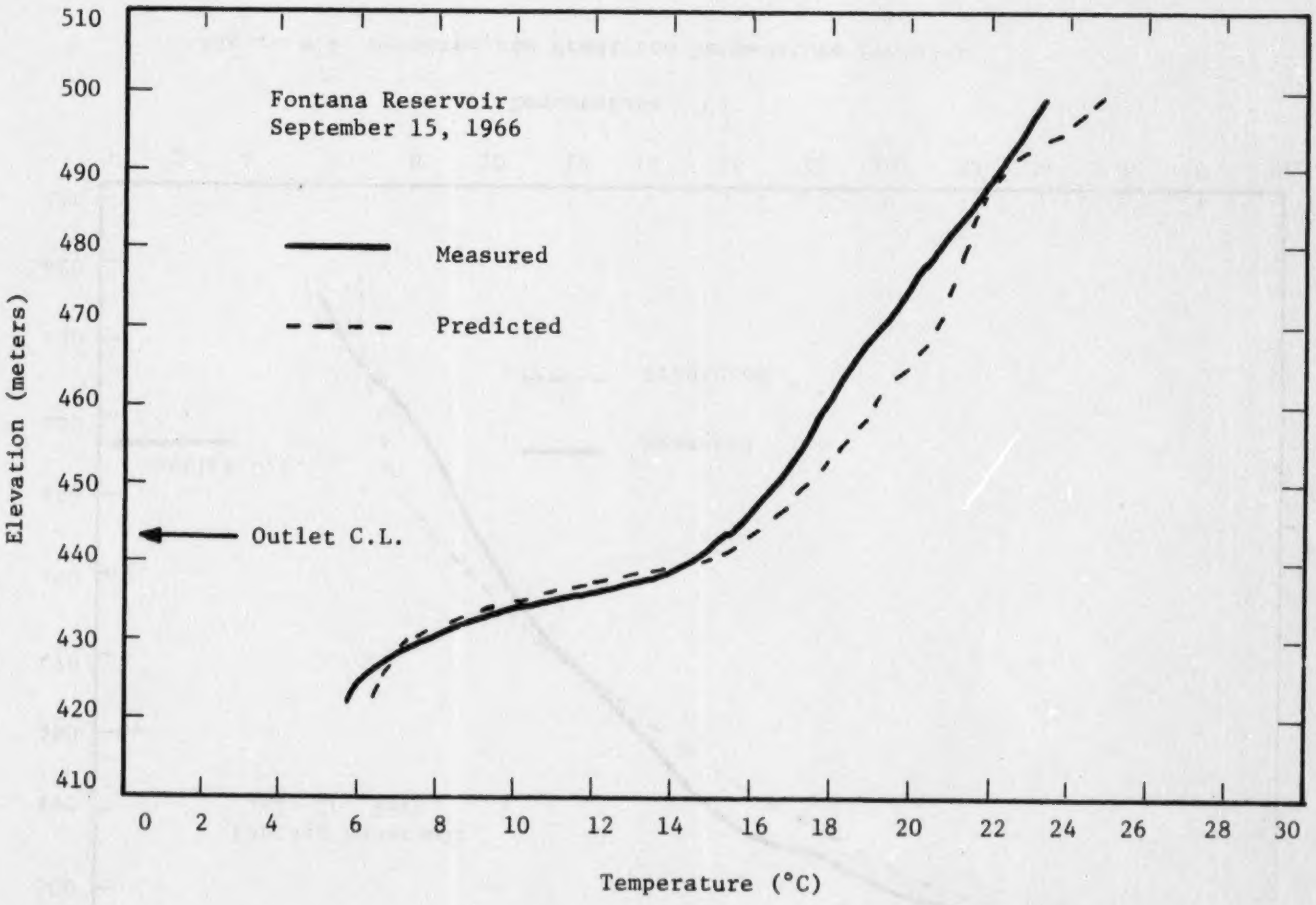


Figure 6.5 Measured and Predicted Temperature Profiles

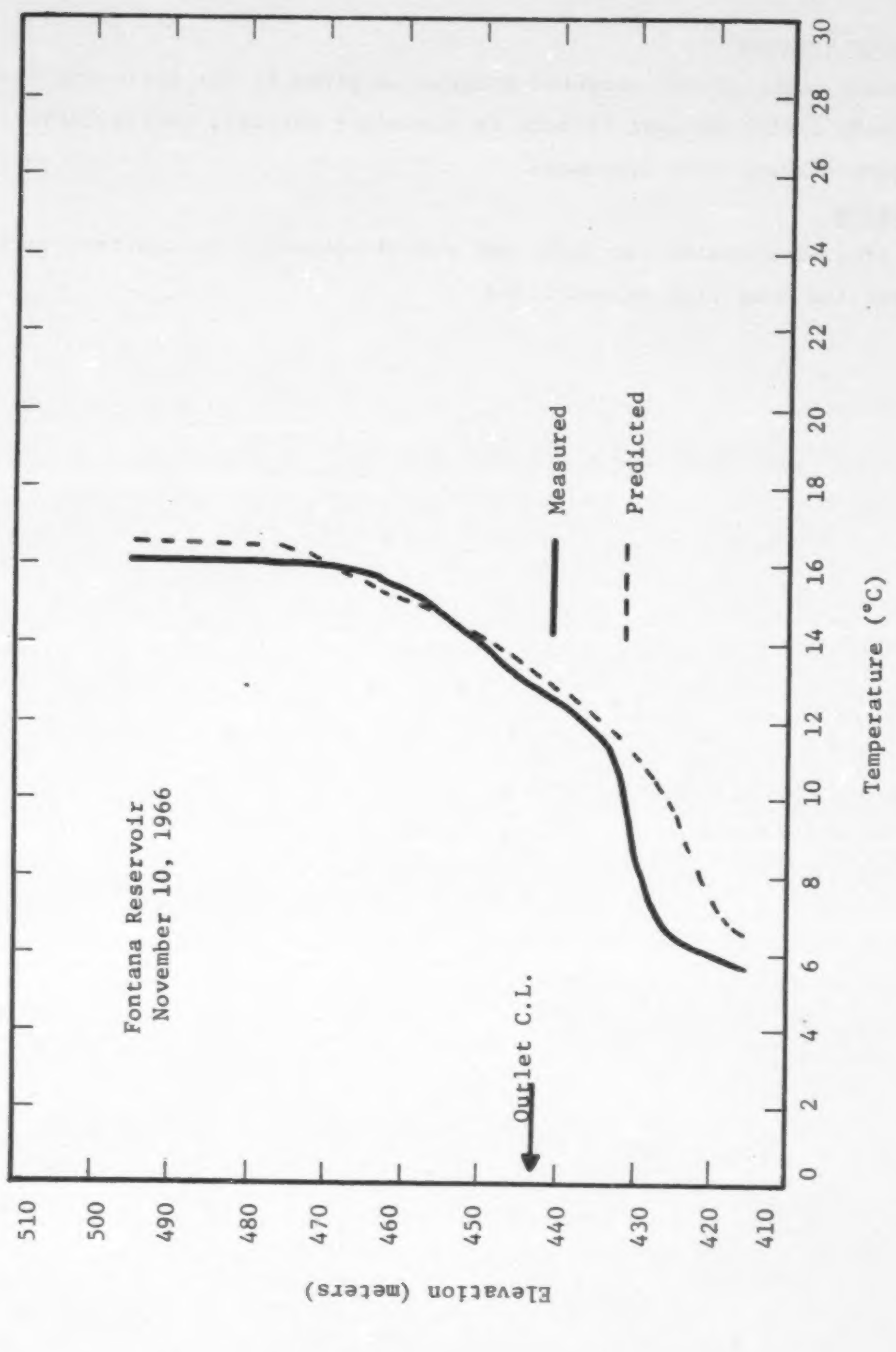


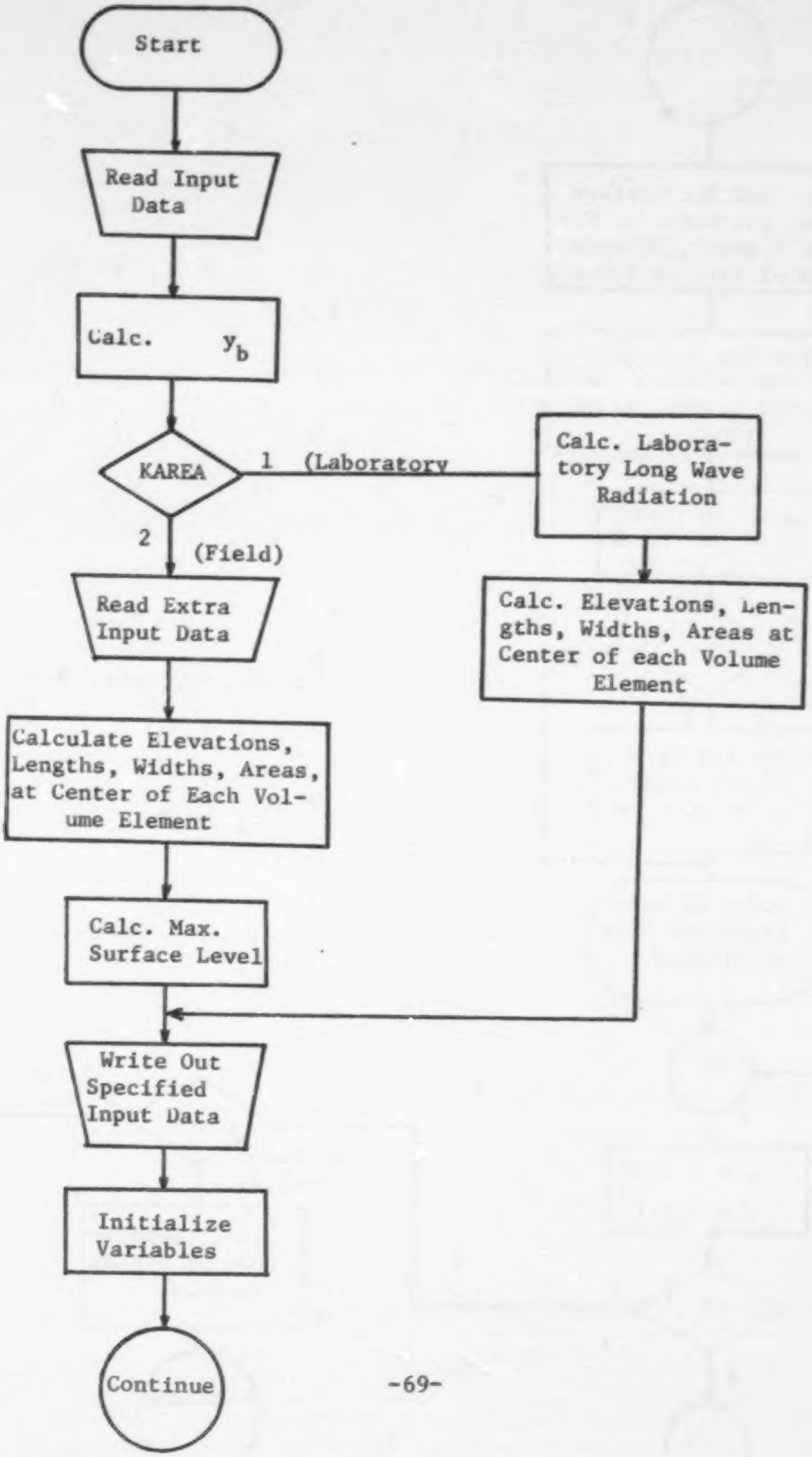
Figure 6.6 Measured and Predicted Temperature Profiles

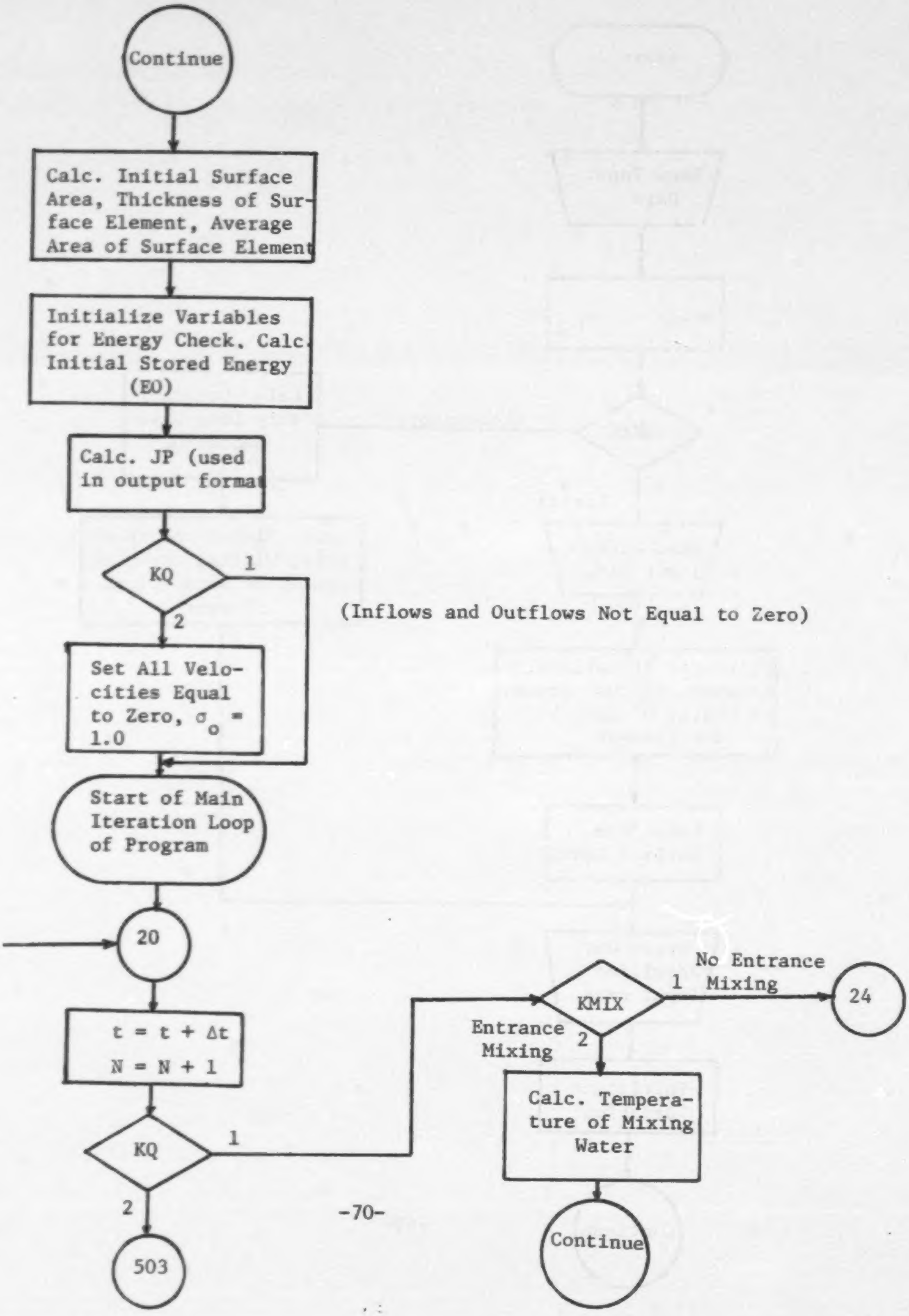
7. The Computer Program

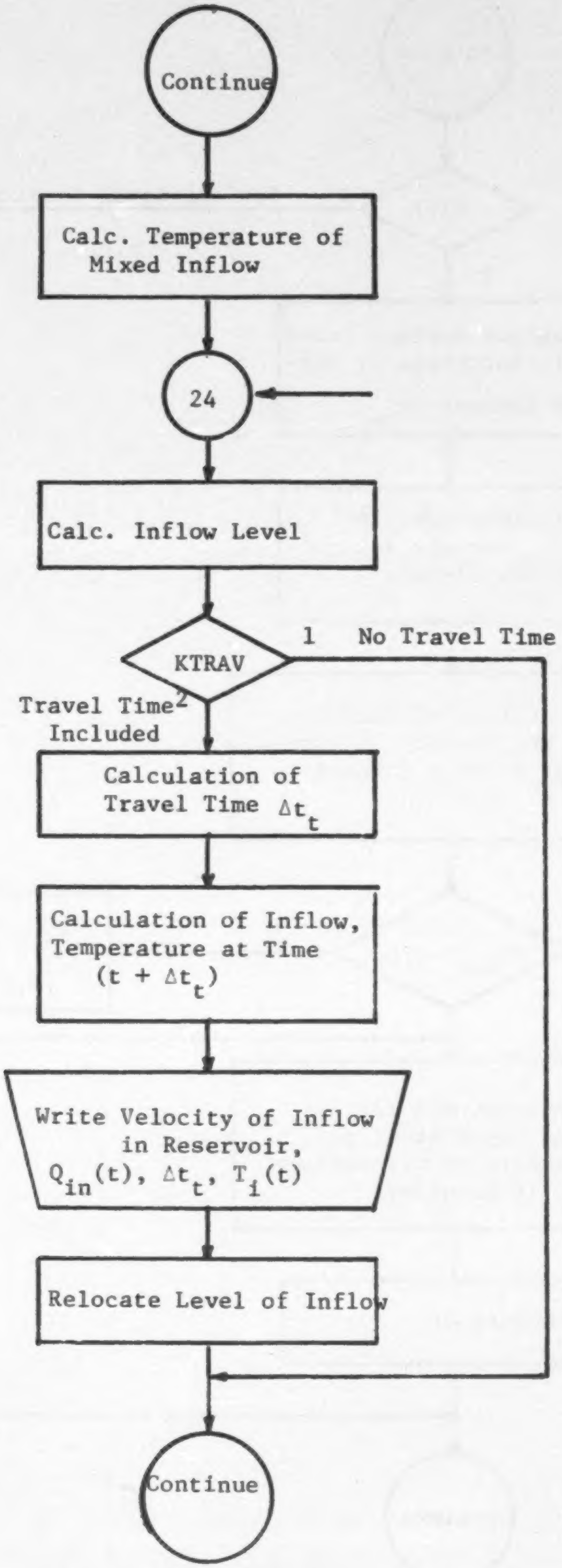
The basic logic of the computer program is given by the following flow charts. However, little attempt is made to reproduce details, particularly where these have already been discussed.

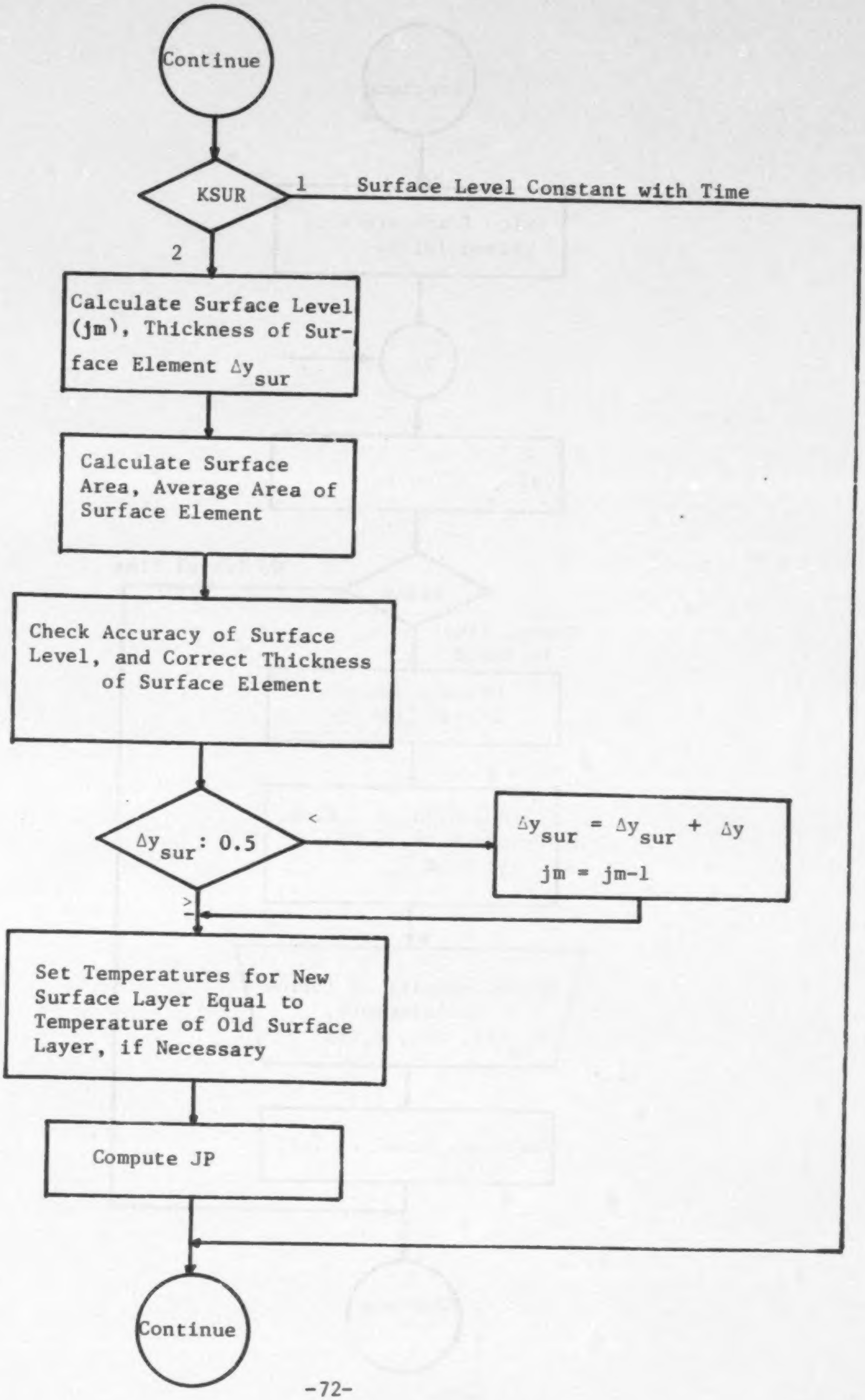
7.1 Main Program

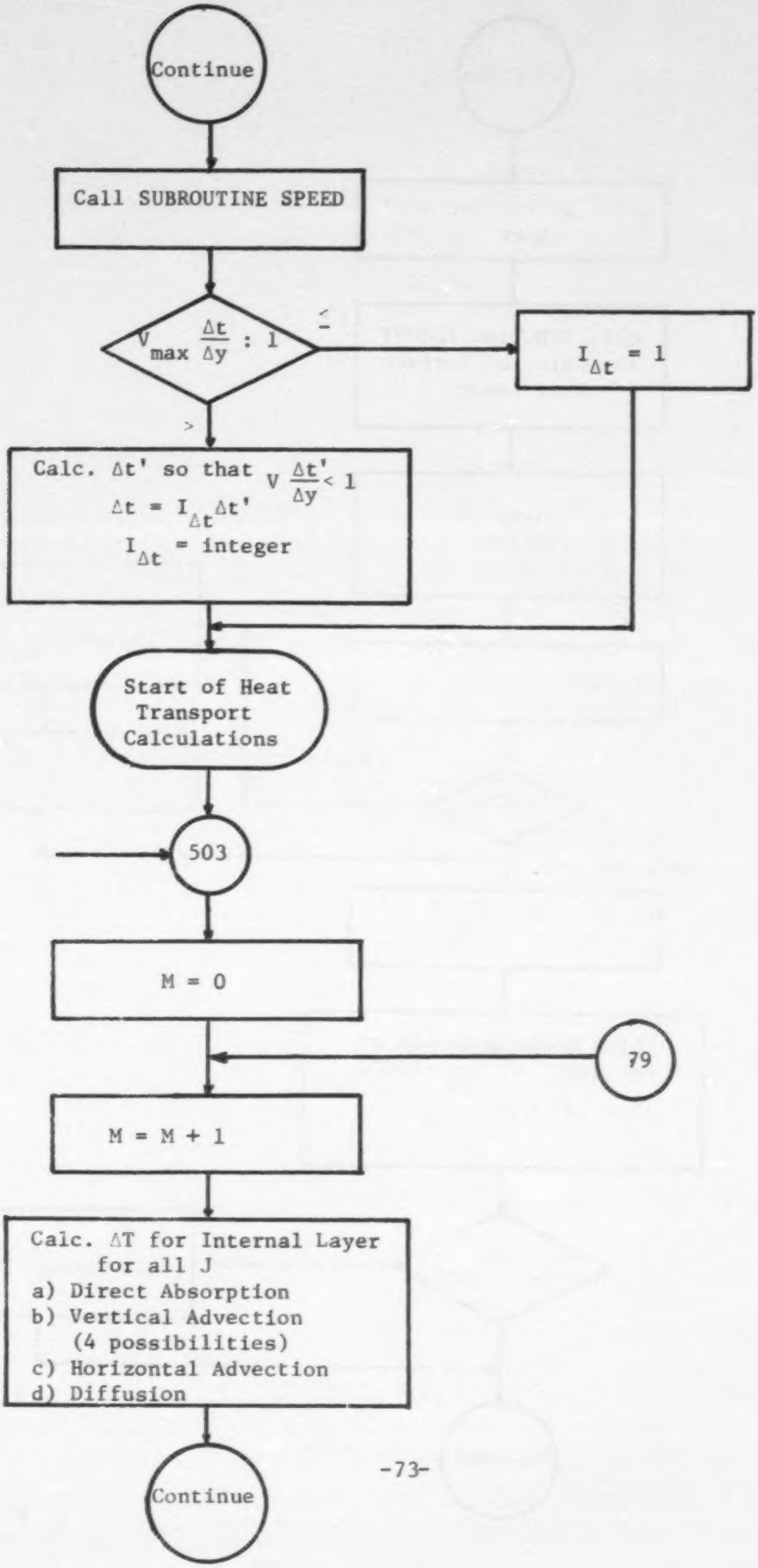
This program contains the input and output commands, initializes variables, and carries out the heat flow calculations.

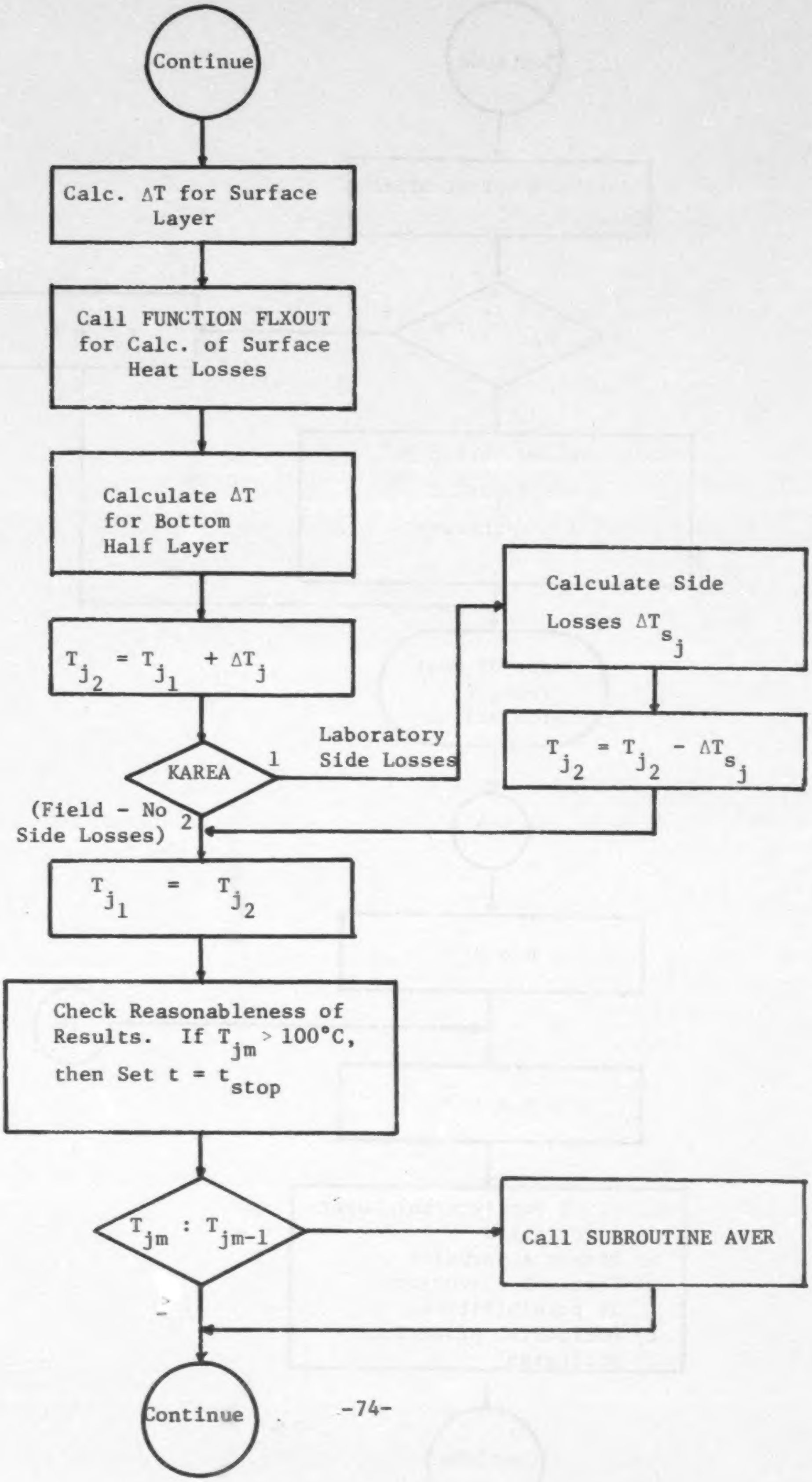

Start
Read Input Data
Calc. y_b
KAREA
1 (Laboratory
Calc. Laboratory Long Wave Radiation
Calc. Elevations, Lengths, Widths, Areas at Center of each Volume Element
2
(Field)
Read Extra Input Data
Calculate Elevations, Lengths, Widths, Areas, at Center of Each Volume Element
Calc. Max. Surface Level
Write Out Specified Input Data
Initialize Variables
Continue

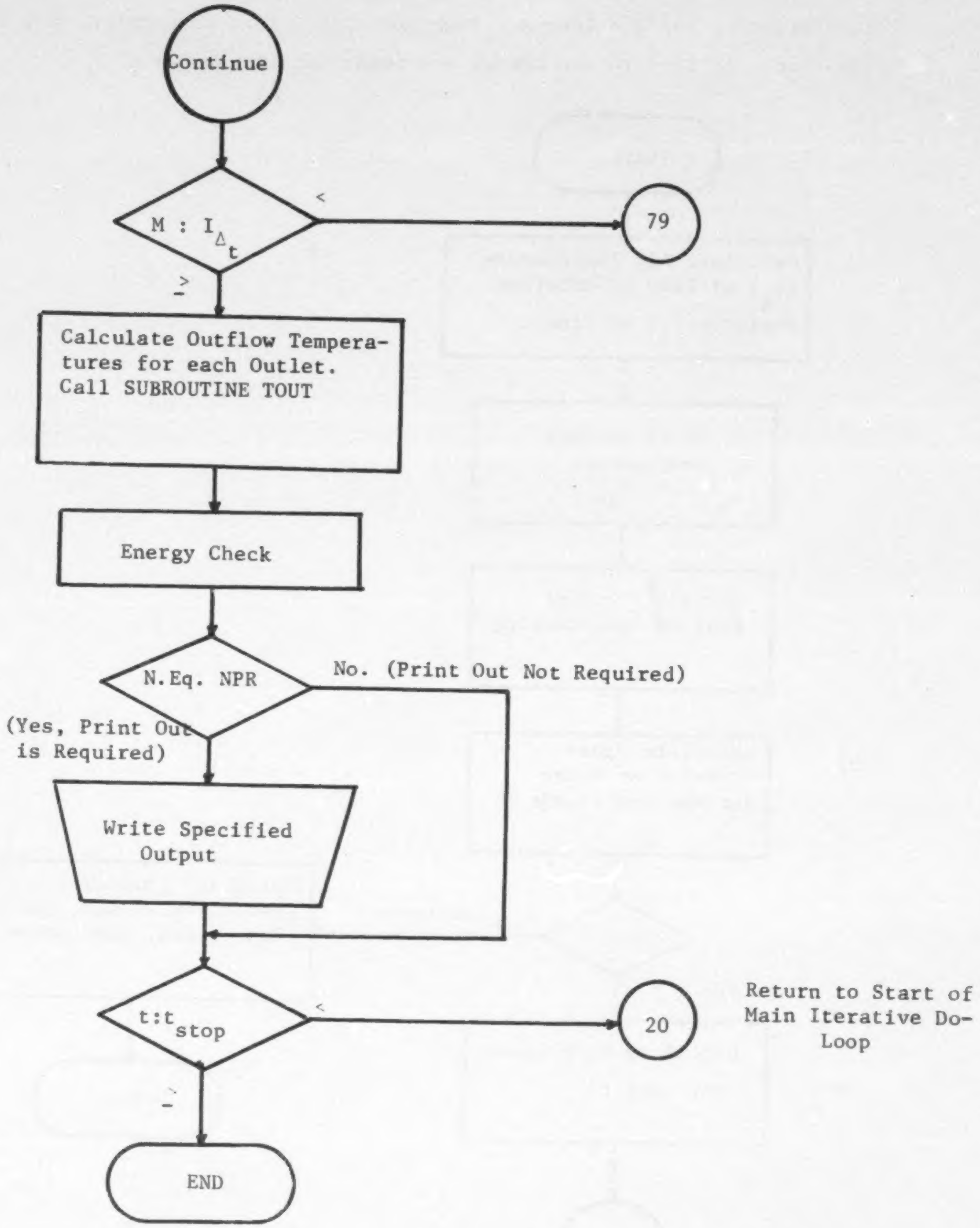

Continue
Calc. Initial Surface Area, Thickness of Surface Element, Average Area of Surface Element
Initialize Variables for Energy Check, Calc. Initial Stored Energy (EO)
Calc. JP (used in output format
KQ
1
2
(Inflows and Outflows Not Equal to Zero)
Set All Velocities Equal to Zero, σ_o = 1.0
Start of Main Iteration Loop of Program
20
t = t + Δt
N = N + 1
KQ
1
2
503
KMIX
1
No Entrance Mixing
24
Entrance Mixing
2
Calc. Temperature of Mixing Water
Continue


Continue
Calc. Temperature of Mixed Inflow
24
Calc. Inflow Level
KTRAV
1 No Travel Time
Travel Time Included 2
Calculation of Travel Time Δt_t
Calculation of Inflow, Temperature at Time $(t + \Delta t_t)$
Write Velocity of Inflow in Reservoir, $Q_{in}(t)$, Δt_t, $T_i(t)$
Relocate Level of Inflow
Continue


Continue
KSUR
1
Surface Level Constant with Time
2
Calculate Surface Level (jm), Thickness of Surface Element Δy_{sur}
Calculate Surface Area, Average Area of Surface Element
Check Accuracy of Surface Level, and Correct Thickness of Surface Element
Δy_{sur} : 0.5
<
$\Delta y_{sur} = \Delta y_{sur} + \Delta y$
jm = jm-1
>
Set Temperatures for New Surface Layer Equal to Temperature of Old Surface Layer, if Necessary
Compute JP
Continue

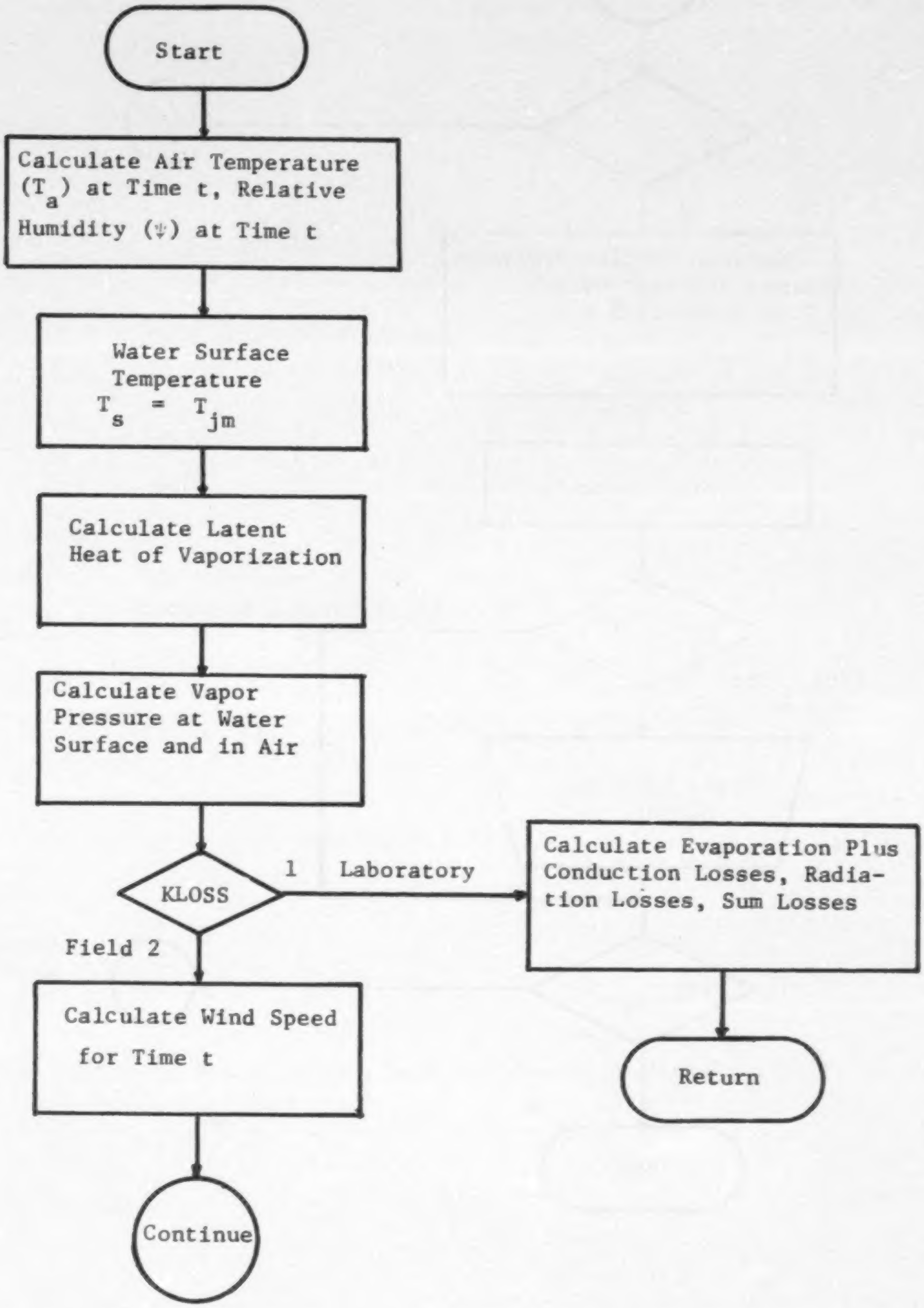

Continue
Call SUBROUTINE SPEED
$V_{max} \frac{\Delta t}{\Delta y} : 1$
$\leq$
$I_{\Delta t} = 1$
>
Calc. $\Delta t'$ so that $V \frac{\Delta t'}{\Delta y} < 1$
$\Delta t = I_{\Delta t} \Delta t'$
$I_{\Delta t}$ = integer
Start of Heat Transport Calculations
503
M = 0
79
M = M + 1
Calc. ΔT for Internal Layer for all J
a) Direct Absorption
b) Vertical Advection (4 possibilities)
c) Horizontal Advection
d) Diffusion
Continue

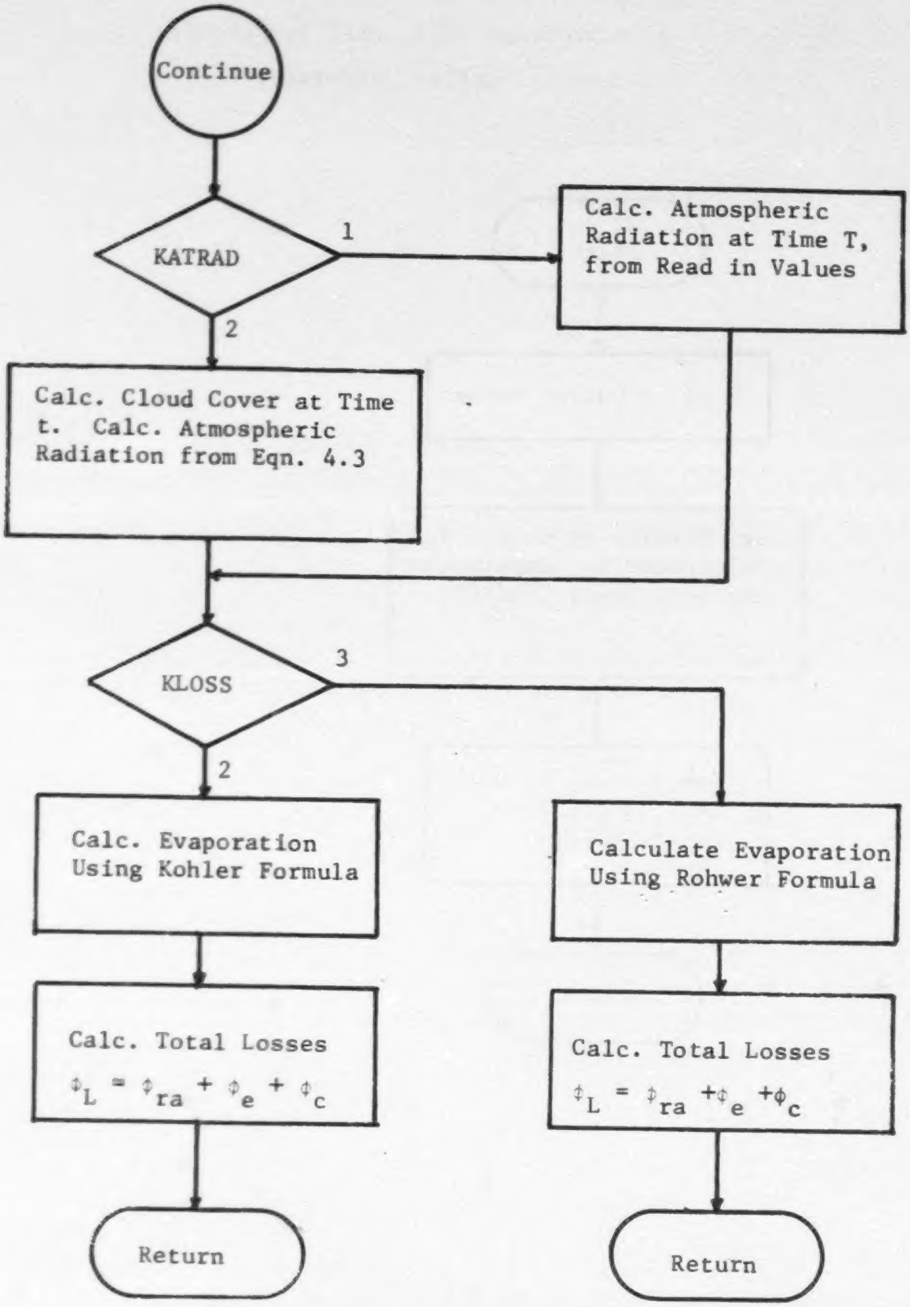

Continue
Calc. ΔT for Surface Layer
Call FUNCTION FLXOUT for Calc. of Surface Heat Losses
Calculate ΔT for Bottom Half Layer
$T_{j_2} = T_{j_1} + \Delta T_j$
KAREA
1
Laboratory Side Losses
Calculate Side Losses ΔT_{s_j}
$T_{j_2} = T_{j_2} - \Delta T_{s_j}$
2
(Field - No Side Losses)
$T_{j_1} = T_{j_2}$
Check Reasonableness of Results. If $T_{jm} > 100°C$, then Set $t = t_{stop}$
$T_{jm} : T_{jm-1}$
>
≤
Call SUBROUTINE AVER
Continue


Continue
M : $I_{\Delta t}$
<
79
≥
Calculate Outflow Temperatures for each Outlet. Call SUBROUTINE TOUT
Energy Check
N.Eq. NPR
No. (Print Out Not Required)
(Yes, Print Out is Required)
Write Specified Output
t:t_{stop}
<
20
Return to Start of Main Iterative Do-Loop
≥
END

7.2 Function FLXOUT (N)

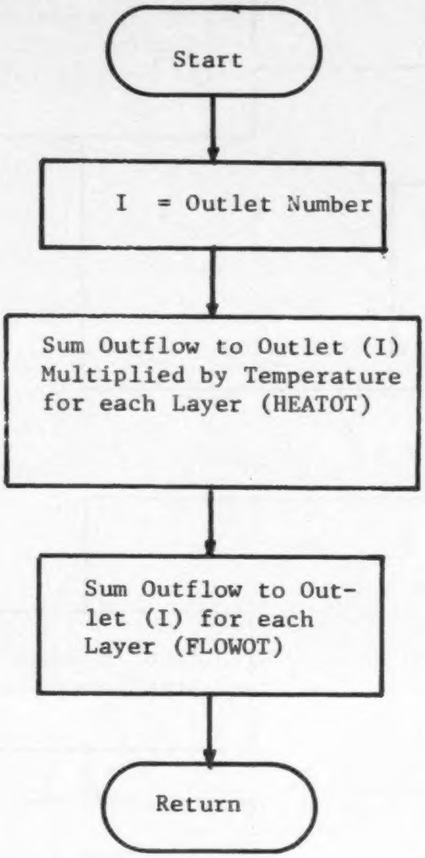
Calculation of Surface Losses ϕ_L due to Evaporation, Conduction, and Radiation. If Evaporation Losses are Negative, Assume Zero.


Start
Calculate Air Temperature (T_a) at Time t, Relative Humidity (ψ) at Time t
Water Surface Temperature $T_s = T_{jm}$
Calculate Latent Heat of Vaporization
Calculate Vapor Pressure at Water Surface and in Air
KLOSS
1 Laboratory
Field 2
Calculate Evaporation Plus Conduction Losses, Radiation Losses, Sum Losses
Return
Calculate Wind Speed for Time t
Continue

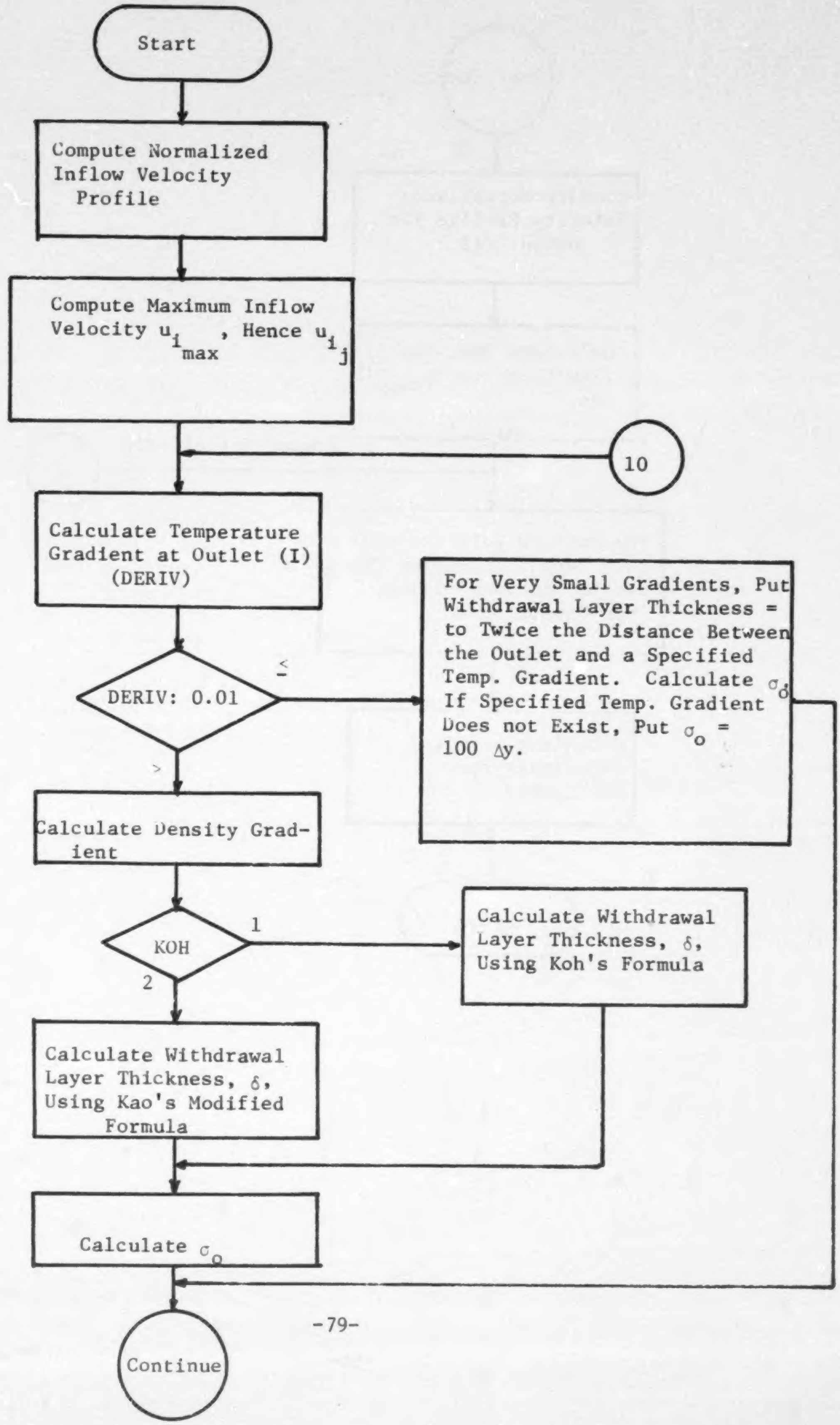

Continue
KATRAD
1
Calc. Atmospheric Radiation at Time T, from Read in Values
2
Calc. Cloud Cover at Time t. Calc. Atmospheric Radiation from Eqn. 4.3
KLOSS
3
2
Calc. Evaporation Using Kohler Formula
Calculate Evaporation Using Rohwer Formula
Calc. Total Losses
$\phi_L = \phi_{ra} + \phi_e + \phi_c$
Calc. Total Losses
$\phi_L = \phi_{ra} + \phi_e + \phi_c$
Return
Return

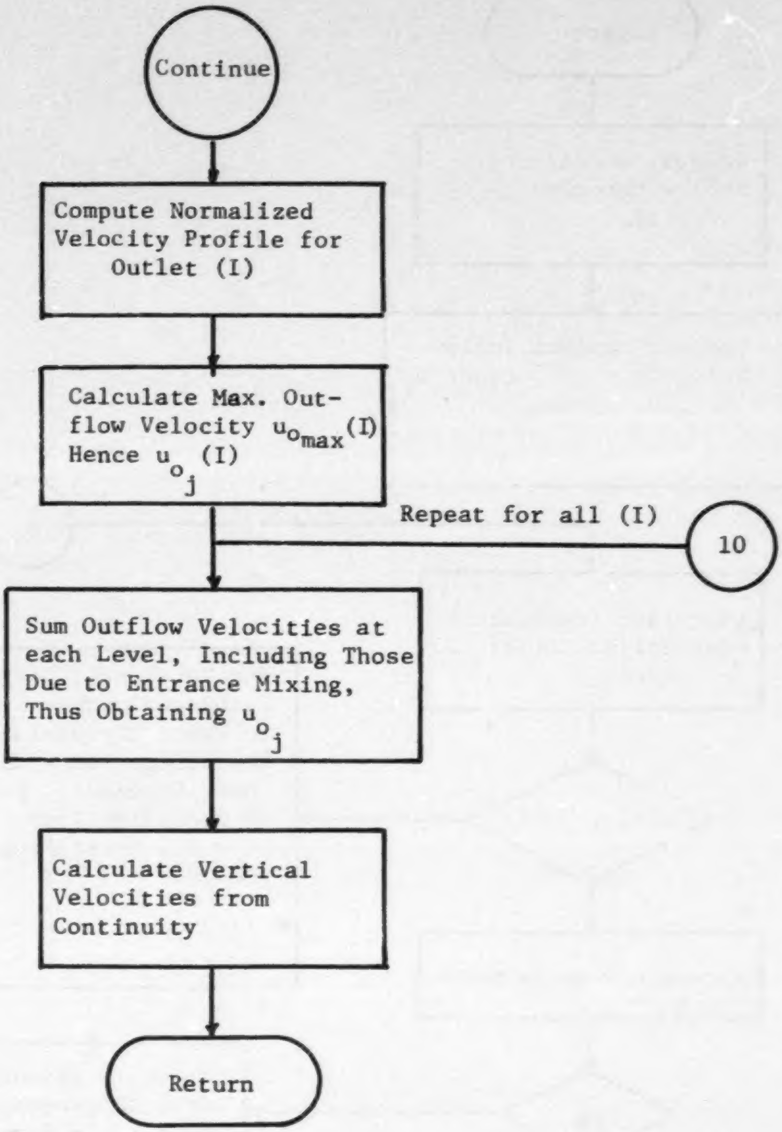
7.3 Subroutine TOUT (HEATOT, FLOWOT)

Compute Outflow Temperature


Start
I = Outlet Number
Sum Outflow to Outlet (I) Multiplied by Temperature for each Layer (HEATOT)
Sum Outflow to Outlet (I) for each Layer (FLOWOT)
Return

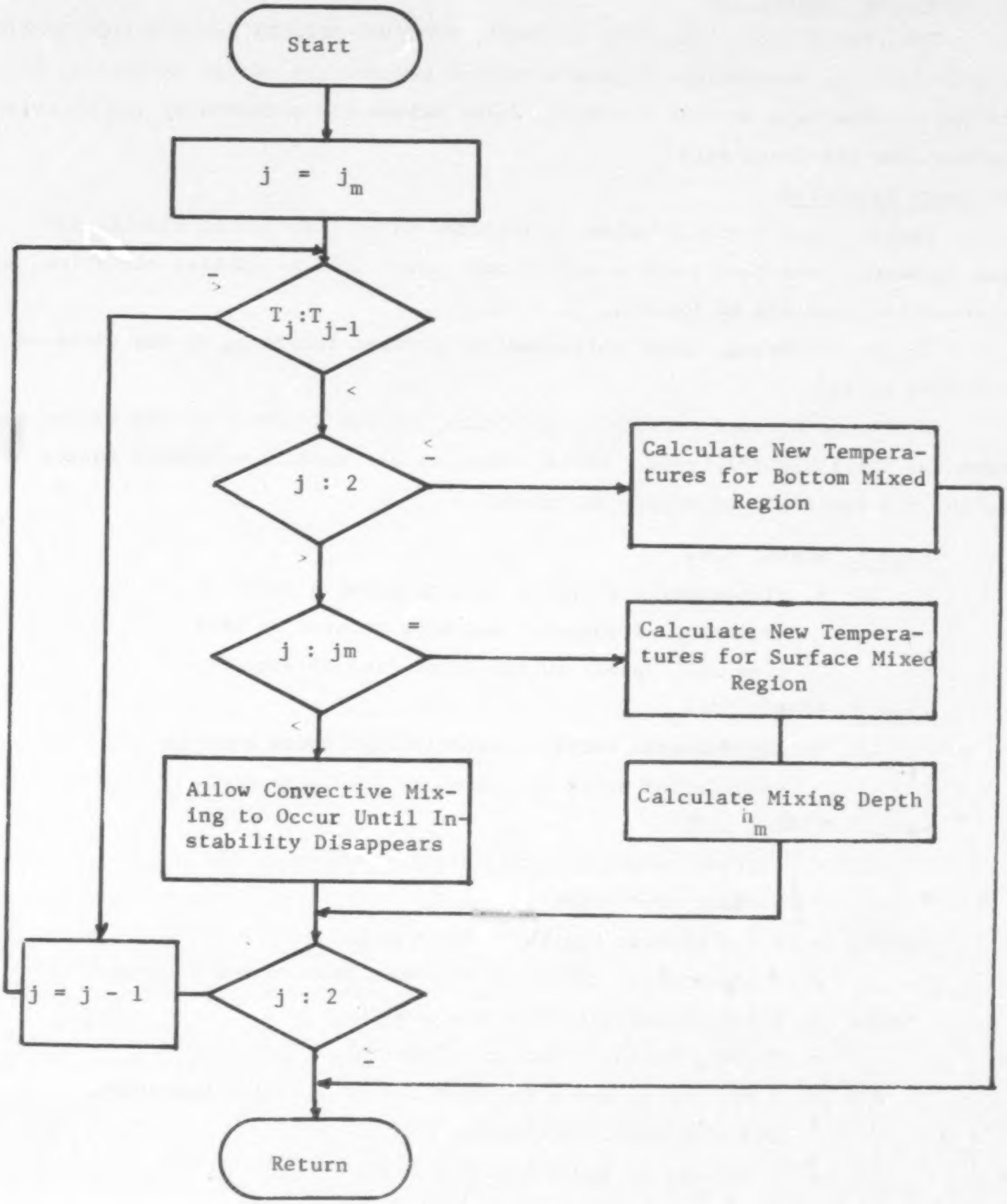
7.4 Subroutine SPEED(N). Calculate Velocities


Start
Compute Normalized Inflow Velocity Profile
Compute Maximum Inflow Velocity $u_{i_{max}}$, Hence u_{i_j}
10
Calculate Temperature Gradient at Outlet (I) (DERIV)
DERIV: 0.01
≤
>
For Very Small Gradients, Put Withdrawal Layer Thickness = to Twice the Distance Between the Outlet and a Specified Temp. Gradient. Calculate σ_δ. If Specified Temp. Gradient Does not Exist, Put σ_o = 100 Δy.
Calculate Density Gradient
KOH
1
2
Calculate Withdrawal Layer Thickness, δ, Using Koh's Formula
Calculate Withdrawal Layer Thickness, δ, Using Kao's Modified Formula
Calculate σ_o
Continue


Continue
Compute Normalized Velocity Profile for Outlet (I)
Calculate Max. Outflow Velocity $u_{o_{max}}(I)$ Hence $u_{o_j}(I)$
Repeat for all (I)
10
Sum Outflow Velocities at each Level, Including Those Due to Entrance Mixing, Thus Obtaining u_{o_j}
Calculate Vertical Velocities from Continuity
Return

7.5 SUBROUTINE AVER

Convective Mixing in Region of Instabilities. Complete Profile Checked


Start
j = j_m
$T_j : T_{j-1}$
≥
<
j : 2
≤
>
Calculate New Temperatures for Bottom Mixed Region
j : jm
=
<
Calculate New Temperatures for Surface Mixed Region
Calculate Mixing Depth h_m
Allow Convective Mixing to Occur Until Instability Disappears
j = j - 1
j : 2
≤
Return

7.6 Remaining Subprograms

FUNCTION TTIN(N), FUNCTION FLXIN(N), FUNCTION QQIN(N) and FUNCTION QOUT(N,I) all calculate the appropriate values of inflow temperature, solar radiation, inflow rate and outflow rate at time $t = N\Delta t$. These values are obtained by linear interpolation from the input data.

7.7 Input Variables

Sample input to the program is provided in Section 7.9 to clarify the input formats. Note that surface elevations, apart from an initial elevation, are not essential, and can be ignored, if necessary.

In the following, input variables are grouped according to the cards on which they appear.

Where options are available, asterisks are put in front of the option recommended for the field reservoir. Where constants are used, recommended values of the constant for the field reservoir are given.

Card 1, FORMAT 20A4

WH = Alphanumeric variable used to print a title at beginning of output. Anything printed on this card will appear as the first line of output.

Card 2, FORMAT 20A4

WH = Alphanumeric variable used to list units used in computation prior to output at each time step.

Card 3, FORMAT 16I5

JM = Initial number of grid points = number of the surface grid point.

** KATRAD = 1 Atmospheric radiation is read in.
= 2 Atmospheric radiation is calculated in the program.

KSUR = 1 for a constant surface elevation.
** = 2 for a variable surface elevation.

KOH = 1 for use of Koh's Equation 2.6 or 2.7, for computing the withdrawal thickness.
** = 2 for use of Kao's Equation 2.10.

** KQ = 1 for computations with inflow and outflow.
= 2 for computation with no inflow or outflow.

KLOSS = 1 for Rohwer laboratory evaporation formula.
= 2 for Kohler field evaporation formula (Equation 4.11).
** = 3 for Rohwer field evaporation formula (Equation 4.10).
NPRINT = Number of time steps between print outs of calculations.
KAREA = 1 for laboratory reservoir calculations.
** = 2 for calculations for any other reservoir.
KMIX = 1 for no entrance mixing.
** = 2 to include entrance mixing.
MIXED = Number of grid spaces in surface layer for entrance mixing = 4.
** KTRAV = 1 travel time of water within reservoir is neglected.
= 2 travel time of water within reservoir is accounted for.

Card 4, FORMAT 8F10.5

YSUR = Surface elevation at beginning of calculations.
DY = Distance increment Δy.
DT = Time step, Δt.
TSTOP = Time at which program ceases calculations.
TZERO = Initial isothermal reservoir temperature.
EVPCON = Constant, a, in evaporation formulas of Chapter 4 for KLOSS=1 or 2. For KLOSS=3, EVPCON = 0.01.*

Card 5, FORMAT 8F10.5

SPREAD = Number of outflow standard deviations, σ_o, equal to half the withdrawal thickness (see discussion of Equation 2.10) = 1.96.
SIGMAI = Inflow standard deviation, σ_1, Equation 2.2.
ETA = Radiation absorption coefficient, η, Equation 2.1.
BETA = Fraction of solar radiation absorbed at the water surface, β, Equation 2.1.
RHO = Water density, ρ, = 997 kg m^{-3}.
HCAP = Water specific heat, c, = 0.998 kcal/kg.
DELCON = Half the value of the constant of Equation 2.5 used to predict the withdrawal thickness, δ. For KOH=2, DELCON=0.00461.*

RMIX = Mixing ratio, r_m,(Equation 2.15)= 1.0

Card 6, FORMAT 16I5

NTI = Number of inflow temperatures to be read in.

NTA = Number of air temperatures to be read in.

NSIGH = Number of relative humidities to be read in.

NFIN = Number of insolation values to be read in.

NSURF = Number of surface elevations to be read in.

NDD = Number of values of the diffusion coefficient to be read in = 2.

NQI = Number of inflow rates to be read in.

NQO = Number of outflow rates to be read in.

NOUT = Number of outlets.

Card 7, FORMAT 8F10.5

DTTI = Time interval between input values of TI.

DTTA = Time interval between input values of TA.

DTSIGH = Time interval between input values of SIGH.

DTFIN = Time interval between input values of FIN.

DSURF = Time interval between input values of SURF.

DTDD = Time interval between input values of DD(= TSTOP for constant diffusion coefficient.)

DTQI = Time interval between input values of QI.

DTQO = Time interval between input values of QO.

Card Group 8, FORMAT 8F10.5

TI = Values of inflow temperatures, T_{in}.

Card Group 9, FORMAT 8F10.5

TA = Values of air temperature, T_a.

Card Group 10, FORMAT 8F10.5

SIGH = Values of relative humidities, ψ, in decimal form.

Card Group 11, FORMAT 8F10.5

FIN = Values of insolation, ϕ_o.

Card Group 12, FORMAT 8F10.5

SURF = Values of surface elevations, y_s.

Card Group 13, FORMAT 8F10.5

DD = Values of diffusion coefficients, D = 0.0125 m^2/day.

Card Group 14, FORMAT 8F10.5

QI = Values of inflow rates, Q_i.

Card Group 15, FORMAT 8F10.5

QO = Values of outflow rates, Q_o.

Card Group 16, FORMAT 16I5

LOUT = Numbers of grid points corresponding to outlet elevations.

Card Group 17, FORMAT 8F10.5

ELOUT = Outlet elevations.

Card Group 18, FORMAT 3F12.2

SLOPE = Slope of reservoir bottom =0.0 if KTRAV = 1.

GRAV = Acceleration due to gravity = 7.315×10^{10} m/day^2.

VISCOS = Kinematic viscosity = 0.0864 m^2/day,

Card Group 19, FORMAT 8F10.5

THICK1 = Observed thickness of inflow layer when traveling along the reservoir bottom =0.0 if KTRAV = 1.

THICK2 = Observed thickness of inflow layer when traveling horizontally = 0.0 if KTRAV = 1.

The following parameters are read in when KAREA = 2. (i.e. for field reservoir)

Card 20, FORMAT 16I5

NAA = Number of areas to be read in.

NXXL = Number of lengths to be read in.

NWIND = Number of wind values to be read in.

NATRAD = Number of atmospheric radiation values to be read in.

JMP = Number of grid points for which program variables should be initialized. (This should be the maximum value of JM expected to occur in the calculations.)

Card 21, FORMAT 8F10.5

DAA = Vertical distance interval between input values of AA.

DXXL = Vertical distance interval between input values of XXL.

DTWIND = Time interval between input values of WIND.

DATRAD = Time interval between input values of ATRAD.

AAB = Elevation of first (lowest) value of AA.

XXLB = Elevation of first (lowest) value of XXL.

Card Group 22, FORMAT 8F10.5

AA = Values of horizontal cross-sectional areas, A.

Card Group 23, FORMAT 8F10.5

XXL = Values of reservoir lengths, L.

Card Group 24, FORMAT 8F10.5

WIND = Values of wind speeds, W.

Read in Card Group 25 when KATRAD = 1

Card Group 25, FORMAT 8F 10.5

ATRAD = Values of atmospheric radiation, ϕ_a.

Read in Card Groups 26, 27 when KATRAD = 2.

Card Group 26, FORMAT F10.5, I5

DCLOUD = Time interval between input values of CLOUD.

NCLOUD = Number of cloud percentages to be read in.

Card Group 27, FORMAT 8F10.5

CLOUD = Percentage of sky covered by clouds.

7.8 Computer Program

```
$JOB            RYAN,KP=29,TIME=5,PAGES=99,RUN=CHECK
C RESERVOIR STRATIFICATION PROGRAM,  1971.
C     MAIN PROGRAM
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QOMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),ELOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),E0,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV,DYSUR,AYSUR
      COMMON DCLOUD,CLOUD(366),KATRAD,III
      DIMENSION WH(20),AA(102),XXL(102)
C READ IN ALL DATA FOR PROGRAM.
      READ (5,900) (WH(I),I=1,20)
      WRITE(6,900) (WH(I),I=1,20)
      READ (5,900) (WH(I),I=1,20)
      READ (5,901) JM,KATRAD,KSUR,KOH ,KQ,KLOSS,NPRINT,KAREA,KMIX,
     1MIXED,KTRAV
      READ (5,902) YSUR,DY,DT,TSTOP,TZERO,EVPCON
      READ (5,902) SPREAD,SIGMAI,ETA,BETA,RHO,HCAP,DELCON,RMIX
      READ (5,901) NTI,NTA,NSIGH,NFIN,NSURF,NDD,NQI,NQO,NOUT
      READ (5,902) DTTI,DTTA,DTSIGH,DTFIN,DSURF,DTDD,DTQI,DTQO
      READ (5,902) (TI(I),I=1,NTI)
      READ (5,902) (TA(I),I=1,NTA)
      READ (5,902) (SIGH(I),I=1,NSIGH)
      READ (5,902) (FIN(I),I=1,NFIN)
      READ (5,902) (SURF(I),I=1,NSURF)
      READ (5,902) (DD(I),I=1,NDD)
      READ (5,902) (QI(I),I=1,NQI)
      DO 3001 I=1,NOUT
```

PAGE
1

```
 3001 READ(5,902)(QO(N,I),N=1,NQO)
      READ(5,901)(LOUT(I),I=1,NOUT)
      READ(5,902)(ELOUT(I),I=1,NOUT)
      READ(5,903) SLOPE,GRAV,VISCOS
      READ (5,902) THICK1,THICK2
      YBOT=ELOUT(1)-DY*FLOAT(LOUT(1)-1)
      GO TO (4,2), KAREA
C READ IN DATA FOR OTHER THAN LABORATORY RESERVOIR IF INDICATED.
    2 READ(5,901) NAA,NXXL,NWIND,NATRAD,JMP
      READ (5,902) DAA,DXXL,DTWIND,DATRAD,AAB,XXLB
      READ (5,902) (AA(I),I=1,NAA)
      READ(5,902)(XXL(I),I=1,NXXL)
      READ (5,902) (WIND(I),I=1,NWIND)
      GO TO (9,10),KATRAD
    9 READ (5,902) (ATRAD(I),I=1,NATRAD)
      GO TO 11
   10 READ(5,901) DCLOUD,NCLOUD
      READ(5,902)(CLOUD(I),I=1,NCLOUD)
   11 DO 3 I=1,JMP
      EL(I) = YBOT+DY*FLOAT(I-1)
      RA = (EL(I)-AAB)/DAA
      L = RA
      A(I) = AA(L+1)+(RA-FLOAT(L))*(AA(L+2)-AA(L+1))
      RA = (EL(I)-XXLB)/DXXL
      L = RA
      XL(I)=XXL(L+1)+(RA-FLOAT(L))*(XXL(L+2)-XXL(L+1))
    3 B(I)=A(I)/XL(I)
      GO TO 5
    4 JMP = JM+IFIX((33.0-YSUR)/DY+0.5)
C CALCULATION OF LONG WAVE RADIATION IN LABORATORY
      AR = 0,7888E-10     *(TA(1)+273.16)**4
      DO 8 I=1,JMP
      B(I) = 30.48
      EL(I) = YBOT+DY*FLOAT(I-1)
      IF (EL(I)-22.4) 6,7,7
    6 XL(I) = 10.0*(EL(I)+87.0)
```

```
      GO TO 8
    7 XL(I) = 1093.5
    8 A(I) = XL(I)*30.48
    5 CONTINUE
      WRITE (6,903) (WH(I),I=1,20)
      WRITE (6,904) JM,YSUR,RHO
      WRITE(6,905)(LOUT(I),ELOUT(I),I=1,NOUT)
      WRITE (6,906) DY,YBOT,ETA
      WRITE (6,907) DT,TZERO,BETA
      WRITE (6,908) KTRAV,SIGMAI,HCAP
      WRITE (6,909) TSTOP,SPREAD
      WRITE (6,910) KATRAD,KSUR,K0H ,KQ,KLOSS,KAREA,EVPCON,DELCON,KMIX
      WRITE (6,923) MIXED,RMIX
C INITIALIZE MANY VARIABLES.
      DO 850 N=1,360
      QIN(N)=0.0
      TIN(N)=0.0
  850 CONTINUE
      DO 851 I=1,JMP
      T(I,1) = TZERO
  851 QQMIX(I)=0.0
      DTT=DT
      NPR=0
      JXM=JM
      N = 0
      JMIXB = JM-MIXED
      QMIX = 0.0
      ET = 0.0
      RAD = 0.0
      EVAP = 0.0
      TAIR = 0.0
      EPSIL = 0.0
      HAFDEL = 0.0
      JIN = JM
      CUMQIN=0.0
      CUMQOT=0.0
      DYSUR=YSUR-EL(JM)+DY/2.0
      IF(YSUR-EL(JM)) 858,858,859
  858 AYSUR=A(JM)-(DY/2.0-DYSUR)*(A(JM)-A(JM-1))/DY
      GO TO 860
  859 AYSUR=A(JM)+(DYSUR-DY/2.0)*(A(JM+1)-A(JM))/DY
  860 SAREA=(AYSUR+(A(JM)+A(JM-1))/2.0)/2.0
      SAREA1=SAREA
      DYSUR1=DYSUR
      JM1=JM
C INITIALIZE VARIABLES USED IN ENERGY CHECK
      E2=0.0
      E3=0.0
      E0=A(1)/2.0+SAREA*DYSUR/DY
      JMM=JM-1
      DO 13 I=2,JMM
   13 E0=E0+A(I)
      E0=E0*DY*TZERO*RHO*HCAP
      IF(JM-60) 15,15,16
   15 JP = JM
      GO TO 17
   16 JP=60
   17 GO TO (20,18), KQ
   18 UIMAX(1)=0.0
      UOMAX(1) = 0.0
      TS=0.0
      DO 19 J=1,JM
      UI(J,1) = 0.0
      UO(J,1)=0.0
   19 V(J,1) = 0.0
      SIGMAO = 1.0
C STATEMENT 20 IS BEGINNING OF MAIN ITERATION LOOP OF PROGRAM.
   20 N=N+1
      ET=ET+DT
      GO TO (21,503),KQ
   21 GO TO (24,22), KMIX
C MIX INFLOW WATER IF INDICATED.
```

```
    22 TP=0.0
       DO 23 J=JMIXB,JM
    23 TP = TP+T(J,1)
       TP = TP/FLOAT(MIXED+1)
       TS=(TTIN(N)+TP*RMIX)/(1.0+RMIX)
       GO TO 25
    24 TS=TTIN(N)
  25   CONTINUE
  C  LOCATE ACTUAL LEVEL OF DAYS INPUT
       DO 27 I=1,JM
       J = JM+1-I
       IF (TS-T(J,1)) 27,30,30
    27 CONTINUE
    30 JIN=J+1
       IF(JIN-JM) 32,32,33
    33 JIN=JM
    32 CONTINUE
       GO TO (46,47),KTRAV
  C CALCULATION OF TRAVEL TIME
  C VELF=DOWNSLOPE VELOCITY,HVELF=HORIZONTAL VELOCITY
    47 JXM=JM
       QLIT=QQIN(N)*(1.0+RMIX)/B(JM)
       IF(JM-2-JIN) 870,870,871
   870 VELF=QLIT/THICK1
       JIN=JM
       XLAG=XL(JM)/VELF
       GO TO 872
   871 DELRHO=6.6E-06*((T(JM,1)-4.0)**2-(TS-4.0)**2)/2.0
       GPRIME=GRAV*DELRHO
       GO TO (873,874),KAREA
   874 SLOPE=(EL(JM)-EL(JIN))/(XL(JM)-XL(JIN))
  873  CONTINUE
       DFLOW=1.92*(QLIT*VISCOS/GPRIME/SLOPE)**0.33
       VELF=QLIT/DFLOW
       HVELF=QLIT/THICK2
       SLDIST=FLOAT(JM-JIN)*DY/SLOPE
```

```
      XLAG=SLDIST/VELF+XL(JIN)/HVELF
  872 LAGTIM(N)=XLAG/DT
      ML=N+LAGTIM(N)
      QIN(ML)=QIN(ML)+QQIN(N)
      TIN(ML)=(TIN(ML)*(QIN(ML)-QQIN(N))+TTIN(N)*QQIN(N))/QIN(ML)
      WRITE(6,875) VELF,QIN(N),LAGTIM(N),TIN(N)
  875 FORMAT(2F12.3,I5,F12.3)
      TP=0.0
      DO 1023 J=JMIXB,JM
 1023 TP=TP+T(J,1)
      TP=TP/FLOAT(MIXED+1)
      TS=(TIN(N)+TP*RMIX)/(1.0+RMIX)
C  RE LOCATE LEVEL OF INFLOW WATER,
      DO 4745 I=1,JM
      J=JM+1-I
      IF(TS-T(J,1)) 4745,4746,4746
 4745 CONTINUE
 4746 JIN=J+1
      IF(JIN-JM) 4747,4747,4748
 4748 JIN=JM
 4747 CONTINUE
      GO TO 48
   46 QIN(N)=QQIN(N)
      TIN(N)=TTIN(N)
C COMPUTATIONS WHEN SURFACE ELEVATION VARIES WITH TIME.
   48 GO TO (45,31),KSUR
   31 JJM=JM
      CUMQIN=CUMQIN+QIN(N)*DT
       DO 332 I=1,NOUT
  332 CUMQOT=CUMQOT+QOUT(N,I)*DT
      QIO=CUMQIN-CUMQOT
      IF(QIO) 34,34,35
   35 SUM=-SAREA1*DYSUR1
      DO 36 M=1,JM
      SUM=SUM+A(JM1+M-1)*DY
      IF(QIO-SUM) 37,37,36
   36 CONTINUE
   34 SUM=DYSUR1*SAREA1
      DO 38 M=1,JM
      IF(ABS(QIO)-SUM) 39,39,38
   38 SUM=SUM+A(JM1-M)*DY
   37 YSUR=EL(JM1)+(M-0.5)*DY+(QIO-SUM)/A(JM1+M-1)
      GO TO 40
   39 YSUR=EL(JM1)-(M-0.5)*DY+(QIO+SUM)/A(JM1-M+1)
   40 DYS=YSUR-EL(JM1)+DY/2.0
      IF(DYS) 41,42,42
   42 M=IFIX(DYS/DY)
      GO TO 43
   41 M=IFIX(DYS/DY)-1
   43 JM=JM1+M
      DYSUR=YSUR-EL(JM)+DY/2.0
C   CALCULATE MEASURED SURFACE LEVEL
      R=ET/DSURF
      L=R
      RR=R-FLOAT(L)
      SURMES=SURF(L)+RR*(SURF(L+1)-SURF(L))
C CALCULATE SURFACE AREA
      IF(YSUR-EL(JM)) 58,58,59
   58 AYSUR=A(JM)-(DY/2.0-DYSUR)*(A(JM)-A(JM-1))/DY
      GO TO 61
   59 AYSUR=A(JM)+(DYSUR-DY/2.0)*(A(JM+1)-A(JM))/DY
   61 SAREA=(AYSUR+(A(JM)+A(JM-1))/2.0)/2.0
C CHECK ACCURACY OF SURFACE LEVEL
      SUMV=0.0
      JMM=JM-1
      IF(JM-JM1) 510,511,512
  512 DO 513 J=JM1,JMM
  513 SUMV=SUMV+A(J)*DY
  511 SUMV=SUMV+SAREA*DYSUR-SAREA1*DYSUR1
      GO TO 515
  510 JMM1=JM1-1
      DO 514 J=JM,JMM1
  514 SUMV=SUMV+A(J)*DY
      SUMV=-(SUMV+SAREA1*DYSUR1-SAREA*DYSUR)
  515 ERROR=SUMV-QIO
      DYCOR=ERROR/SAREA
      DYSUR=DYSUR-DYCOR
      IF(DYSUR-0.5) 506,506,507
  506 DYSUR=DYSUR+DY
      JM=JM-1
  507 MM=JM-JJM
      IF(MM)44,44,50
   50 DO 51 I=1,MM
      J=JM+1-I
   51 T(J,1)=T(JJM,1)
   44 T(JM,1)=T(JJM,1)
      JMIXB=JM-MIXED
      IF(JM-60) 53,53,54
   53 JP=JM
      GO TO 45
   54 JP=60
   45 CONTINUE
C SUB SPEED COMPUTES WITHDRAWAL THICKNESS AND VELOCITIES AT EACH TIME STEP.
      CALL SPEED(N)
C STABILITY CHECK V*DT IS LESS THAN DY
      VVV=ABS(V(2,1))
      DO 501 J=3,JM
      IF(VVV-ABS(V(J,1)))502,501,501
  502 VVV=ABS(V(J,1))
  501 CONTINUE
      VM=DY/DTT
      IF(VVV-VM) 503,504,504
  504 DT=DY/VVV
      IDT=DTT/DT+1
      DT=DTT/IDT
      GO TO 505
  503 IDT=1
  505 DO 79 M=1,IDT
```

```
C HEAT TRANSPORT CALCULATIONS
      JMM=JM-1
      DO 1114 J=2,JMM
C DIRECT ABSORPTION TERM
      ARJ1=(A(J)+A(J+1))/2.0
      ARJ2=(A(J)+A(J-1))/2.0
      DELTA=(1.0-BETA)*FLXIN(N)*(EXP(-ETA*(YSUR-EL(J)-DY/2.0))*ARJ1-
     1EXP(-ETA*(YSUR-EL(J)+DY/2.0))*ARJ2)/A(J)/DY/HCAP/RHO
C VERTICAL ADVECTION TERM
      IF(V(J,1)) 1160,1160,1161
 1160 IF(V(J+1,1))1170,1170,1171
 1170 DELTB=(V(J,1)*T(J,1)*(A(J)+A(J-1))/2.0-V(J+1,1)*T(J+1,1)*(A(J+1)+
     1A(J))/2.0)/A(J)/DY
      GO TO 1162
 1171 DELTB=(V(J,1)*T(J,1)*(A(J)+A(J-1))/2.0-V(J+1,1)*T(J,1)*(A(J+1)+
     1A(J))/2.0)/A(J)/DY
      GO TO 1162
 1161 IF(V(J+1,1))1172,1172,1173
 1173 DELTB=(V(J,1)*T(J-1,1)*(A(J)+A(J-1))/2.0-V(J+1,1)*T(J,1)*(A(J+1)+
     1A(J))/2.0)/A(J)/DY
      GO TO 1162
 1172 DELTB=(V(J,1)*T(J-1,1)*(A(J)+A(J-1))/2.0-V(J+1,1)*T(J+1,1)*(A(J+1)
     1+A(J))/2.0)/A(J)/DY
C HORIZONTAL ADVECTION TERM
 1162 DELTC=(UI(J,1)*TS-UO(J,1)*T(J,1))*B(J)*DY/A(J)/DY
C DIFFUSION TERM
      DELTD=DD(1)*((T(J+1,1)-T(J,1))/DY*ARJ1-(T(J,1)-T(J-1,1))/DY*ARJ2)
     1/A(J)/DY
      DELT=(DELTA+DELTB+DELTC+DELTD)*DT
 1114 T(J,2)=T(J,1)+DELT
C CALCULATIONS FOR SURFACE LAYER
      IF (V(JM,1))1163,1164,1164
 1164 DELTJM=DT*((1.0-BETA)*FLXIN(N)*(AYSUR-EXP(-ETA*DYSUR)*
     1 (A(JM)+A(JM-1))/2.0)/SAREA/DYSUR/HCAP/RHO+
     1V(JM,1)*(T(JM-1,1)-T(JM,1))*(A(JM)+A(JM-1))/2.0/SAREA/DYSUR
     1+UI(JM,1)*(TS-T(JM,1))*B(JM)/SAREA
     1-DD(1)*(T(JM,1)-T(JM-1,1))/DY*(A(JM)+A(JM-1))/2.0/SAREA/DYSUR
     1+(BETA*FLXIN(N)-FLXOUT(N))*AYSUR/RHO/HCAP/DYSUR/SAREA)
      GO TO 1165
 1163 DELTJM=DT*((1.0-BETA)*FLXIN(N)*(AYSUR-EXP(-ETA*DYSUR)*
     1 (A(JM)+A(JM-1))/2.0)/SAREA/DYSUR/HCAP/RHO+
     1 UI(JM,1)*(TS-T(JM,1))*B(JM)/SAREA
     1-DD(1)*(T(JM,1)-T(JM-1,1))/DY*(A(JM)+A(JM-1))/2.0/SAREA/DYSUR
     1+(BETA*FLXIN(N)-FLXOUT(N))*AYSUR/RHO/HCAP/DYSUR/SAREA)
 1165 T(JM,2)=T(JM,1)+DELTJM
      FLUXOT=FLXOUT(N)
C CALCULATIONS FOR BOTTOM  HALF LAYER
      IF(V(2,1)) 1166,1167,1167
 1167 DELT1=DT*((1.0-BETA)*FLXIN(N)*EXP(-ETA*(YSUR-EL(1)-DY/2.0))*
     1 (A(2)+A(1))/2.0/RHO/HCAP
     2 +UI(1,1)*B(1)*DY/2.0*(TS-T(1,1))
     3+DD(1) *(T(2,1)-T(1,1))*(A(2)+A(1))/2.0/DY)/A(1)/DY*2.0
      GO TO 1168
 1166 DELT1=DT*((1.0-BETA)*FLXIN(N)*EXP(-ETA*(YSUR-EL(1)-DY/2.0))*
     1 (A(2)+A(1))/2.0/RHO/HCAP
     2+UI(1,1)*B(1)*DY/2.0*(TS-T(1,1))-V(2,1)*(A(2)+A(1))/2.0
     2*(T(2,1)-T(1,1))
     3+DD(1) *(T(2,1)-T(1,1))*(A(2)+A(1))/2.0/DY)/A(1)/DY*2.0
 1168 T(1,2)=T(1,1)+DELT1
C SIDE HEAT LOSSES FOR LABORATORY RESERVOIR
      GO TO (1115,1117),KAREA
 1115 DO 1116 J=1,JM
      PHIM=0.79E-10*(T(J,1)+273.0)**4-AR
      DELT=(2.0*(XL(J)+B(J))*PHIM/RHO/HCAP/A(J))*DT
      FLUXOT=FLUXOT+PHIM*2.0*(XL(J)+B(J))*DY/AYSUR
 1116 T(J,2)=T(J,2)-DELT
 1117 DO 1118 J=1,JM
 1118 T(J,1)=T(J,2)
C CHECK REASONABLENESS OF RESULTS.
      IF (ABS(T(JM,2))-100.0) 60,57,57
   57 TSTOP = ET
      GO TO 80
```

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C SUB AVER MIXES SURFACE LAYERS IN THE EVENT OF A SURFACE INSTABILITY.
   60 IF (T(JM,2)+0.01-T(JM-1,2)) 63,79,79
   63 CONTINUE
      CALL AVER(N)
   79 CONTINUE
      DT=DTT
      DO 78 I=1,NOUT
      III=I
      GO TO (115,116),KQ
  116 TOUTC(I)=0.0
      GO TO 78
  115 CALL TOUT(HEATOT,FLOWOT)
      TOUTC(I)=HEATOT/FLOWOT
   78 CONTINUE
C        ENERGY CHECK
      E1=A(1)*DY/2.0*T(1,1)
      JMM=JM-1
      DO 111 J=2,JMM
  111 E1=E1+A(J)*DY*T(J,1)
      E1=E1+SAREA*DYSUR*T(JM,1)
      E1=E1*RHO*HCAP
      E2=E2+FLXIN(N)*AYSUR*DT+QIN(N)*DT*TIN(N)*RHO*HCAP
      E3=E3+FLUXOT*AYSUR*DT
      DO 112 I=1,NOUT
  112 E3=E3+QOUT(N,I)*DT*TOUTC(I)*RHO*HCAP
      ENRAT=(E1-E3)/(E2-E3)
      TENRAT=(E1+E3)/(E2+E0)
      IF(N-NPR) 100,100,80
   80 NPR = NPR+NPRINT
      WRITE (6,900)(WH(I),I=1,20)
      WRITE (6,912) ET,SURMES,TIN(N)
      WRITE (6,913) N,YSUR,TAIR
      WRITE (6,914) JM,EL(JIN),PSI
      WRITE (6,915) JIN,EVAP,FLXIN(N)
      WRITE(6,925) DMIX,AR,WINDY
      WRITE (6,916) FLUXOT,RAD,QIN(N)
   GO TO (85,89), KO
85 F = 2.0*HAFDEL
   WRITE (6,918) EPSIL,F,SIGMAO
   DO 88 I=1,NOUT
88 WRITE (6,917) ELOUT(I),QOUT(N,I),TOUTC(I)
   WRITE(6,926) ENRAT,E1,E2,E3
   GO TO (89,86), KMIX
86 WRITE (6,924) TP,TS,TENRAT
89 WRITE (6,920)
   DO 90 I=1,10
90 WRITE (6,921) (J,EL(J),T(J,1),J=I,JP,10)
   IF(JM-60) 100,100,91
91 WRITE (6,922)
   IF(JM-70) 92,93,93
92 LL = JM
   GO TO 94
93 LL=70
94 DO 95 I=61,LL
95 WRITE (6,921) (J,EL(J),T(J,1),J=I,JM,10)
100 IF (ET-TSTOP) 20,1,1
 1 CONTINUE
900 FORMAT (20A4)
901 FORMAT (16I5)
902 FORMAT (8F10.5)
903 FORMAT(3F12.2)
904 FORMAT (' NUMBER OF GRID POINTS='I3,17X,'SURFACE ELEVATION='F7.2,
  118X,'DENSITY='E12.5)
905 FORMAT (' OUTLET LEVEL='I3,  26X,'OUTLET ELEVATION='F8.2)
906 FORMAT (' DY='F6.2,33X,'BOTTOM ELEVATION='F8.2,18X,'ETA='F6.3)
907 FORMAT (' DT='F6.2,33X,'INITIAL TEMPERATURE='F6.2,17X,'BETA='F5.2)
908 FORMAT (' KTRAV='I5 ,31X,'INFLOW STD. DEV.='F6.2,21X,
  1'HEAT CAPACITY='F8.5)
909 FORMAT (' STOP AT TIME='F7.2,22X,'OUTFLOW SPREAD CONST.='F5.2)
910 FORMAT (' KATRAD='I2,15X,'KSUR='I2,13X,'KOH ='I2,15X,'KQ='I2,16X,
  1'KLOSS='I2,13X,'KAREA='I2/' EVAPORATION CONSTANT='E11.4,10X,
  2 'CONST IN EQN FOR OUTFLOW DELTA='F5.2,7X,'KMIX='I2)
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911 FORMAT ( 'ON='I3,'. ABOUT TO ENTER SUBROUTINE AVER.')
912 FORMAT (   ' ELAPSED TIME='F7.2,22X,'ACTUAL SURFACE ELEVATION='
   1F7.2,11X,'INFLOW TEMPERATURE='F6.2)
913 FORMAT (' NO. OF TIME STEPS='I4,20X,'SURFACE ELEVATION USED='
   1F9.2,11X,'AIR TEMPERATURE='F6.2)
914 FORMAT (' NO. OF GRID POINTS='I3,20X,'ELEVATION OF INFLOW='F7.2,
   116X,'RELATIVE HUMIDITY='F5.2)
915 FORMAT (' LEVEL OF INFLOW='I3,23X,'EVAPORATION FLUX='E12.5,14X,
   1'INSOLATION FLUX='E12.5)
916 FORMAT (' HEAT LOSS FLUX='E12.5,15X,'RADIATION FLUX='E12.5,
   116X,'INFLOW RATE='F11.1)
917 FORMAT (' OUTLET ELEVATION='F10.5,15X,' OUTFLOW RATE='F10.1,19X,
   1 ' OUTFLOW TEMPERATURE='F6.2'C')
918 FORMAT (' EPSILON='E11.4,23X,'WITHDRAWAL THICKNESS='F7.2,15X,
   1'OUTFLOW STD. DEV.='F6.2)
920 FORMAT (/7('  J ELEV TEMP(C)  '))
921 FORMAT(7(I3,F6.1,F6.2,3X))
922 FORMAT (/' TIME FROM BEGINNING OF CALCULATIONS FOR THIS DATA SET='
   1I3,' MINUTES,'I3,' SECONDS.')
923 FORMAT (' NO. GRID SPACES IN MIXED LAYER='I3,8X,'MIXING RATIO='
   1F5.2)
924 FORMAT (' TEMP OF MIXING LAYER='F6.2,15X,'MIXED INFLOW TEMP='
   1F6.2,19X,'TOTAL ENERGY RATIO='F9.5)
925 FORMAT (' MIXING DEPTH='F5.2,24X,'ATMOSPHERIC RADIATION='E12.5,
   1 9X,'WIND SPEED='F5.2)
926 FORMAT(' ENERGY RATIO='F7.3, 5X,'ENERGY STORED='E12.5, 5X,'ENERGY
   1INFLOW='E12.5, 3X,'ENERGY OUTFLOW='E12.5)
    CALL EXIT
    END
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      FUNCTION FLXOUT(N)
C CALCULATION OF SURFACE LOSSES DUE TO EVAPORATION, CONDUCTION, AND RADIATION.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QOMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),ELOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),E0,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV,DYSUR,AYSUR
      COMMON DCLOUD,CLOUD(366),KATRAD
C KLOSS = 1 FOR LABORATORY USING ROHWER FORMULA.
C         2 FOR FIELD USING KOHLER FORMULA.
C         3 FOR FIELD USING ROHWER FORMULA.
      ET=DTT*FLOAT(N)
      R = ET/DTTA
      L = R
      RR = R-FLOAT(L)
      TAIR=TA(L)+RR*(TA(L+1)-TA(L))
      R = ET/DTSIGH
      L = R
      RR = R-FLOAT(L)
      PSI=SIGH(L)+RR*(SIGH(L+1)-SIGH(L))
      TS = T(JM,1)
      H = 597.3-0.56*TS
C PARABOLIC APPROXIMATION FOR VAPOR PRESSURES IN MM HG.
      ES = 0.0418*TS*TS-0.6216*TS+13.0068
      EA = PSI*(0.0418*TAIR*TAIR-0.6216*TAIR+13.0068)
      DE = ES-EA
      GO TO (15,20,20), KLOSS
C CALCULATIONS FOR LABORATORY USE ROHWER FORMULA.
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   15 CHI = RHO*(H*DE+TS*HCAP*DE)
      EVAP = CHI*EVPCON
      CONDUC=RHO*EVPCON*269.1*(TS-TAIR)
      IF(EVAP)1,1,2
    1 EVAP=0.0
    2 EVAP=EVAP+CONDUC
C UNITS OF RADIATION ARE CAL/CM-CM-MIN.
      AR = 0.7888E-10    *(TAIR+273.16)**4
      RAD = 0.7888E-10    *(273.16+TS)**4-AR
      W = 0.0
      FLXOUT=EVAP+RAD
      RETURN
C FOR FIELD DATA, WIND SPEED IS IN M/SEC.
   20 R = ET/DTWIND
      L = R
      W=WIND(L)+(R-FLOAT(L))*(WIND(L+1)-WIND(L))
      WINDY=W
C CALCULATION OF ATMOSPHERIC RADIATION
C UNITS OF RADIATION ARE KCAL/M-M-DAY.
      GO TO (7,8),KATRAD
    7 R=ET/DATRAD
      L = R
      AR=ATRAD(L)+(R-FLOAT(L))*(ATRAD(L+1)-ATRAD(L))
      RAD = 1.13587E-6*(TS+273.16)**4-AR
      GO TO 9
    8 R=ET/DCLOUD
      L=R
      CC=CLOUD(L)+(R-FLOAT(L))*(CLOUD(L+1)-CLOUD(L))
      RAD=1.13587E-6*((TS+273.16)**4-0.937E-5*(TAIR+273.16)**6*(1.0+
     1 0.017*CC**2))
    9 GO TO (15,25,30), KLOSS
C CALCULATION OF FIELD EVAPORATION USING KOHLER FORMULA.
C VAPOR PRESSURES IN MB.
   25 DE = DE/0.750062
      EVAP = H*DE+HCAP*DE*TS
      EVAP = EVPCON*RHO*W*EVAP
      CONDUC=RHO*EVPCON*W*372.0*(TS-TAIR)
      IF(EVAP)3,3,4
    3 EVAP=0.0
    4 EVAP=EVAP+CONDUC
      FLXOUT=EVAP+RAD
      RETURN
C CALCULATION OF FIELD EVAPORATION USING ROHWER FORMULA.
   30 CHI = RHO*(H*DE+TS*HCAP*DE)
      FW = 0.0308+0.0185*W
      EVAP = CHI*FW*EVPCON
      CONDUC=RHO*EVPCON*269.1*(TS-TAIR)*FW
      IF(EVAP)5,5,6
    5 EVAP=0.0
    6 EVAP=EVAP+CONDUC
      FLXOUT =EVAP+RAD
      RETURN
      END
      SUBROUTINE TOUT(HEATOT,FLOWOT)
C COMPUTE WEIGHTED AVERAGE OF OUTFLOW TEMPERATURE.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QOMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),ELOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),E0,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV,DYSUR,AYSUR
      COMMON DCLOUD,CLOUD(366),KATRAD,III
      I=III
      HEATOT=T(JM,1)*B(JM)*UOT(JM,I)*DYSUR+T(1,1)*B(1)*UOT(1,I)*DY/2.0
      FLOWOT=B(JM)*UOT(JM,I)*DYSUR+B(1)*UOT(1,I)*DY/2.0
      JMM=JM-1
      DO 2 J=2,JMM
      HEATOT=HEATOT+UOT(J,I)*B(J)*DY*T(J,1)
    2 FLOWOT=FLOWOT+UOT(J,I)*B(J)*DY
      IF(FLOWOT.EQ.0.0) FLOWOT=1.0
      CONTINUE
      RETURN
      END
      SUBROUTINE SPEED(N)
C COMPUTATION OF VERTICAL AND SOURCE AND SINK VELOCITIES.
C ALSO. COMPUTATION OF WITHDRAWAL THICKNESS.
C SOURCE AND SINK VELOCITIES ARE ASSUMED TO HAVE GAUSSIAN DISTRIBUTION.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QQMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),FLOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),E0,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV,DYSUR,AYSUR
      COMMON DCLOUD,CLOUD(366),KATRAD
C  COMPUTE INFLOW VELOCITY
C  COMPUTE EXPONENTIAL FACTOR
      DO 1 I=1,JM
      S(I)=(DY*FLOAT(I-1))**2
      ARGI=S(I)/2.0/SIGMAI/SIGMAI
      IF(ARGI-20.0)4,4,5
    4 EX(I)=EXP(-ARGI)
      GO TO 1
    5 EX(I)=0.0
    1 CONTINUE
      DO 2 J=1,JM
      II=IABS(J-JIN)+1
    2 EXI(J)=EX(II)
C  COMPUTE MAX INFLOW VEL.
      VOLIN=EXI(1)*B(1)*DY/2.0+EXI(JM)*B(JM)*DYSUR
      JMM=JM-1
      DO 3 J=2,JMM
    3 VOLIN=VOLIN+EXI(J)*B(J)*DY
```

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      UIMAX(1)=QIN(N)/VOLIN
      GO TO (8,7),KMIX
    7 UIMAX(1)=UIMAX(1)*(1.0+RMIX)
    8 DO 6 J=1,JM
    6 UI(J,1)=UIMAX(1)*EXI(J)
C     COMPUTE OUTFLOW VELOCITIES
      DO 10 LT=1,NOUT
      JOUT=LOUT(LT)
C COMPUTE WITHDRAWAL THICKNESS.
C NOTE THAT ONLY HALF THE WITHDRAWAL THICKNESS IS COMPUTED.
      DERIV = (T(JOUT+1,1)-T(JOUT-1,1))/2.0/DY
      IF(DERIV-0.010) 11,11,15
   11 JOUT1=JOUT+2
C CUTOFF DUE TO SHARP CHANGE IN DENSITY GRADIENT
      DO 12 J=JOUT1,JMM
      IF((T(J+1,1)-T(J,1))/DY-.05)12,13,13
   12 CONTINUE
      SIGMAO=100.0*DY
      GO TO 19
   13 HAFDEL=FLOAT(J-JOUT)*DY
      SIGMAO=HAFDEL/SPREAD
   19 JOUT2=JOUT-2
      DO 21 I=1,JOUT2
      J=JOUT2+2-I
      IF((T(J,1)-T(J-1,1))/DY-0.05) 21,21,22
   21 CONTINUE
      GO TO 14
   22 HAFD1=FLOAT(JOUT-J)*DY
      SIGM1=HAFD1/SPREAD
      IF(SIGM1.LT.SIGMAO) SIGMAO=SIGM1
      GO TO 14
C APPROXIMATING FORMULA USED FOR DENSITY IS RHO=1.0-0.00000663*(T-4.0)**2.
   15 EPSIL= 2.0*(T(JOUT,1)-4.0)/(151000.0-(T(JOUT,1)-4.0)**2)*DERIV
      GO TO (17,16),KOH
C CALCULATION OF WITHDRAWAL THICKNESS USING KAO FORMULA.
   16 QPUW=QOUT(N,LT)/B(JOUT)
```

```
      HAFDEL = DELCON*SQRT(OPUW)/EPSIL**0.25
      GO TO 18
C CALCULATION OF WITHDRAWAL THICKNESS USING KOH FORMULA.
   17 HAFDEL = DELCON/EPSIL**0.1666667
   18 SIGMAO = HAFDEL/SPREAD
      IF(SIGMAO) 20,20,14
   20 SIGMAO=1.0
   14 CONTINUE
C    COMPUTE EXP. FACTOR
      DO 100 I=1,JM
      S(I)=(DY*FLOAT(I-1))**2
      ARGO=S(I)/2.0/SIGMAO/SIGMAO
      IF(ARGO-20.0) 104,105,105
  104 OX(I)=EXP(-ARGO)
      GO TO 100
  105 OX(I)=0.0
  100 CONTINUE
      DO 110 J=1,JM
      IO=IABS(J-JOUT)+1
  110 EXO(J)=OX(IO)
C FIRST COMPUTE MAXIMUM VELOCITIES, THEN OTHERS.
      VOLOUT=EXO(1)*B(1)*DY/2.0+EXO(JM)*B(JM)*DYSUR
      JMM=JM-1
      DO 120 J=2,JMM
  120 VOLOUT=VOLOUT+EXO(J)*B(J)*DY
      UOMAX(LT)=QOUT(N,LT)/VOLOUT
      DO 130 J=1,JM
  130 UOT(J,LT)=UOMAX(LT)*EXO(J)
   10 CONTINUE
      DO 36 J=1,JM
      GO TO (31,32),KMIX
   32 IF(J-JMIXB) 31,33,33
   33 QQMIX(J)=QIN(N)*RMIX/(MIXED+1)
      UO(J,1)=QQMIX(J)/B(J)/DY
      IF(J.EQ.JM) UO(JM,1)=UO(J,1)*DY/DYSUR
      GO TO 36
   31 UO(J,1)=0.0
      DO 35 LT=1,NOUT
   35 UO(J,1)=UO(J,1)+UOT(J,LT)
   36 CONTINUE
C COMPUTE VERTICAL ADVECTIVE VELOCITY
      V(1,1)=0.0
      V(2,1)=(UI(1,1)-UO(1,1))*B(1)*DY/(A(1)+A(2))
      JMX=JM+1
      DO 500 J=3,JMX
      V(J,1)=(V(J-1,1)*(A(J-2)+A(J-1))/2.0+(UI(J-1,1)-UO(J-1,1))*B(J-1)
     1*DY)/(A(J)+A(J-1))*2.0
  500 CONTINUE
      RETURN
      END
      SUBROUTINE AVER(N)
C PERFORMS CONVECTIVE MIXING OF SURFACE LAYERS.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UD(102,1)
      COMMON QIN(460),TIN(460),QQMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),ELOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),ED,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV,DYSUR,AYSUR
      COMMON DCLOUD,CLOUD(366),KATRAD
      AV1=0.0
      AV2=0.0
      JMM=JM-1
      DO 5 I=1,JMM
      J=JM-I+1
      JJ=J-1
      IF(T(J,1)-T(JJ,1)) 6,7,7
    6 CONTINUE
      IF(J-2) 8,8,9
    8 T(2,1)=(T(2,1)*A(2)+T(1,1)*A(1)/2.0)/(A(2)+A(1)/2.0)
      T(1,1)=T(2,1)
      GO TO 7
    9 DO 10 K=1,JJ
      KJ=J+1-K
      KJJ=KJ-1
      IF(JM-KJ) 2,2,3
    2 AREA=(AYSUR+(A(JM)+A(JM-1))/2.0)/2.0*DYSUR/DY
      GO TO 4
    3 AREA=A(KJ)
    4 AV1=AV1+T(KJ,1)*AREA
```

```
      AV2=AV2+AREA
      TAV=AV1/AV2
      IF(TAV-T(KJJ,1)) 10,20,20
   10 CONTINUE
   20 IF(J.EQ.JM) MIXH=K
      DMIX=(MIXH-1)*DY+DY/2.0
      DO 30 L=KJ,J
   30 T(L,1)=TAV
    7 AV1=0.0
      AV2=0.0
    5 CONTINUE
      RETURN
      END
      FUNCTION TTIN(N)
C COMPUTE INFLOW TEMPERATURE FROM READ IN VALUES.
C LINFAR INTERPOLATION BETWEEN READ IN VALUES.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QQMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),ELOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),E0,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV
      ET=DTT*FLOAT(N)
      R = ET/DTTI
      L = R
      RR = R-FLOAT(L)
      TTIN=TI(L)+RR*(TI(L+1)-TI(L))
      RETURN
      END
      FUNCTION FLXIN(N)
C COMPUTE INCOMING SOLAR RADIATION FROM READ IN VALUES.
C READ IN VALUES TREATED AS A STEP FUNCTION.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KO,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QOMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),ELOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),EO,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV
      ET=DTT*FLOAT(N)
      R = ET/DTFIN
      L = R
      FLXIN = FIN(L)
      RETURN
      END
      FUNCTION QQIN(N)
C COMPUTE INFLOW RATE FROM READ IN VALUES.
C READ IN VALUES TREATED AS A STEP FUNCTION.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAD
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QQMIX(102),MIXH,DMIX,EXI(102),QX(102)
      COMMON NOUT,LOUT(5),ELOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),E0,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV
      ET=DTT*FLOAT(N)
      R = ET/DTQI
      L = R
      QQIN=QI(L)
      RETURN
      END
      FUNCTION QOUT(N,I)
C COMPUTE OUTFLOW RATE FROM READ IN VALUES.
C READ IN VALUES TREATED AS A STEP FUNCTION.
      COMMON T(102,2),EL(102),XL(102),A(102),TI(366),TA(366),SIGH(366)
      COMMON FIN(366),WIND(366),DD(366),QI(366),QO(366,5)
      COMMON UOMAX(5),UIMAX(1),DTTI,DTTA,DTSIGH,DTFIN,DTWIND,DTDD,DTQI
      COMMON DTQO,JM,JOUT,JIN,KSUR,KOH,KQ,KLOSS,YSUR,YOUT,DT,DY
      COMMON TSTOP,EVPCON,SPREAD,SIGMAI,SIGMAO
      COMMON EVAP,RAD,TAIR,PSI,DERIV,HAFDEL,EPSIL
      COMMON YBOT,BETA,DELCON,V(102,1),UI(102,1),DTT
      COMMON RHO,HCAP,KMIX,RMIX,JMIXB,MIXED,QMIX,KAREA,DATRAD,ATRAD(366)
      COMMON AR,WINDY,B(102),S(102),EX(102),EXO(102),UO(102,1)
      COMMON QIN(460),TIN(460),QOMIX(102),MIXH,DMIX,EXI(102),OX(102)
      COMMON NOUT,LOUT(5),FLOUT(5),TOUTC(5),UOT(102,5)
      COMMON SURF(366),GRAV,SLOPE,VISCOS,LAGTIM(366),E0,E1,E2,E3,ET
      COMMON THICK1,THICK2,KTRAV
      ET=DTT*FLOAT(N)
      R = ET/DTQO
      L = R
      QOUT = QO(L,I)
      RETURN
      END
```

7.9 Sample Input Data

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$ENTRY
1FIELD DATA FOR FONTANA RESERVOIR FOR MARCH 1 TO DECEMBER 31, 1966.
0ALL UNITS IN METERS, DAYS, KILOCALORIES, KILOGRAMS, AND DEGREES CENTIGRADE.
   47     1     2     2     1     3    10     2     2     4     1
    492.49         2.0         1.0      305.0         6.7       0.01
1.96         4.0        0.75        0.50         997.0       0.998      0.00461    1.00
  306   306   306   306   306     2   306   306     1
         1.0         1.0         1.0         1.0         1.0       306.0         1.0         1.0
        7.58        7.24        6.93        8.27        8.35        6.34        5.62        5.51
        6.06        6.67        7.61        8.29        9.13        9.96       10.70       10.97
       10.84       10.83       11.41       11.39       10.94       11.36       12.11       11.68
        9.40        8.52        8.25        8.27        8.50        8.73        9.83        9.93
        9.91       10.23       10.93        9.75        9.47        9.55        9.45        9.48
        9.95       10.41       11.63       12.29       12.32       12.66       12.45       12.92
       13.87       13.55       12.81       13.31       13.97       14.25       15.29       15.42
       15.68       15.00       14.55       14.79       14.93       14.30       13.59       12.86
       13.26       13.41       13.93       14.38       15.14       15.11       13.81       12.83
       12.59       12.28       13.28       14.30       13.81       13.86       14.16       14.51
       15.80       16.46       16.97       17.25       16.26       15.73       15.81       15.51
       16.36       17.13       17.06       16.20       15.68       15.31       15.78       16.91
       17.98       18.00       18.37       18.65       18.46       18.00       18.58       20.45
       19.73       19.25       18.53       18.91       19.42       18.07       18.42       18.88
       19.39       19.28       19.34       19.87       19.67       20.57       19.39       19.75
       19.47       19.29       18.76       18.81       20.31       20.81       20.55       20.59
       20.43       21.06       20.75       22.16       23.63       24.24       23.73       23.74
       23.22       21.49       21.64       22.30       22.84       21.37       20.65       20.48
       20.54       21.25       21.19       21.03       21.33       21.08       20.63       19.01
       18.04       18.45       18.44       18.27       18.31       18.48       18.48       18.20
       18.49       18.71       18.48       17.83       17.62       17.74       18.14       18.91
       19.55       20.86       19.96       19.89       19.70       19.54       19.18       19.86
       19.30       18.66       18.48       18.62       19.12       19.58       18.84       18.44
       18.79       18.96       19.04       18.84       19.17       19.08       18.26       18.88
       18.77       19.00       18.76       18.18       17.16       17.37       17.30       17.28
       17.21       16.43       15.36       16.03       16.28       15.85       16.00       16.10
       15.75       15.14       15.89       15.95       16.36       16.32       15.20       13.84
       13.69       14.29       14.44       13.94       13.97       13.80       13.98       14.28
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    14.12     13.78     13.84     14.25     14.28     13.04     13.02     11.74
    11.23     10.82     10.84     11.11     11.58     12.46     12.79     12.56
    12.11     11.81     11.49     10.93     11.38     12.03     10.81      9.20
     8.43      8.81     10.01     10.92     11.14     11.87     11.14     12.52
    12.22     12.04     11.60     10.71      9.91      9.64     10.14     10.27
     9.72      8.65      8.61      8.53      8.04      8.55      9.47      9.08
     8.55      6.68      6.29      6.33      6.46      6.27      5.68      5.26
     6.21      7.78      8.84      9.88      9.19      8.24      7.22      7.02
     6.82      6.47      6.24      6.46      6.49      6.59      6.46      6.31
     6.45      6.63      5.82      4.08      3.76      4.12      5.05      5.38
     4.69      4.82
    6.034     5.248     8.752    11.746     0.281    -3.432    -2.560    -1.432
    1.090     4.079     5.834     7.473     9.306    12.868    11.472    11.003
   11.451    10.478    10.325    10.118    10.673    15.065    13.138     4.107
    2.285     1.821     2.808     1.612     2.176     6.157     6.616     7.283
    7.706     9.062     7.009     4.490     4.008     6.440     5.253     6.247
    3.872     8.892    14.036    14.995    10.948     9.377     7.864     9.398
   14.503    14.329    15.785    16.072    15.669    15.946    16.830    16.717
   15.288    15.481    17.253    15.828    16.199    16.398    14.063    12.950
   12.760    14.871    16.124    17.406    16.865    13.309     9.056    12.204
   13.810    14.753    16.077    14.543    12.711    19.122    17.264    18.814
   18.252    15.990    18.244    19.780    15.585    17.954    17.391    17.497
   19.289    16.884    15.868    11.156    10.545    12.878    15.439    17.855
   19.189    18.040    20.001    20.130    20.709    20.640    19.662    20.206
   19.782    17.334    18.962    18.722    18.485    16.408    18.199    18.628
   19.087    19.119    20.022    20.839    21.466    20.298    21.017    21.295
   20.961    20.126    19.251    21.147    22.369    20.963    22.457    21.289
   20.705    20.616    21.225    22.387    24.086    24.779    23.719    24.490
   21.894    21.837    21.199    23.723    21.759    22.718    20.908    21.449
   20.201    20.539    22.264    22.816    23.756    23.990    22.134    20.767
   19.991    20.521    20.838    20.266    20.037    20.121    20.964    20.303
   21.359    20.835    20.423    21.372    20.924    22.145    22.389    22.619
   23.398    24.036    22.820    21.810    22.092    22.846    21.757    20.887
   18.303    18.157    18.172    17.669    19.054    20.546    18.785    19.387
   19.851    19.873    20.279    20.783    20.950    18.379    18.892    18.478
   18.398    17.520    18.019    16.330    16.854    18.640    15.742    17.059

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  15.840    14.965    16.749    18.101    16.357    14.567    15.396    13.470
  13.559    14.208    18.583    17.673    16.044    15.379    10.724     8.225
  10.174    13.469    13.655     8.635     9.879    11.651    13.383    16.243
   9.510     9.866    12.215    14.964    17.684    14.084     6.452    10.002
   8.749     8.107     7.193    10.727    14.354    14.866    13.859    11.152
   8.250     7.339     8.602     8.783     9.233    10.010     2.928    -1.490
   0.428     5.304    10.523    10.444    10.746    12.747    14.179    12.162
  13.076    10.286    10.962     6.450     5.769     6.126     9.373    10.375
   6.940     3.493     4.233     4.929     5.464     7.803    11.906    10.372
  -0.207    -1.522     1.251     0.795     2.252     0.443    -0.513     1.178
   5.543     9.435    13.233    16.696    10.667     3.067     2.058     1.567
   0.497    -0.226     1.092     1.279     2.979     3.808     3.705     3.997
   5.695     5.164    -4.045    -4.841    -0.781     0.409     4.788    -1.212
  -3.691     1.718
   0.687     0.707     0.899     0.800     0.845     0.989     0.992     0.807
   0.726     0.674     0.660     0.688     0.767     0.730     0.943     0.841
   0.612     0.730     0.661     0.544     0.696     0.669     0.797     0.637
   0.655     0.852     0.654     0.609     0.658     0.569     0.609     0.652
   0.480     0.618     0.835     0.546     0.583     0.597     0.785     0.567
   0.592     0.568     0.681     0.769     0.793     0.795     0.715     0.653
   0.629     0.757     0.755     0.852     0.922     0.796     0.699     0.750
   0.899     0.907     0.857     0.924     0.960     0.929     0.888     0.684
   0.620     0.643     0.670     0.647     0.708     0.767     0.562     0.565
   0.849     0.950     0.789     0.739     0.945     0.781     0.915     0.806
   0.693     0.818     0.861     0.740     0.882     0.871     0.948     0.950
   0.811     0.856     0.671     0.666     0.668     0.683     0.739     0.730
   0.704     0.775     0.771     0.806     0.858     0.806     0.751     0.697
   0.751     0.905     0.744     0.825     0.798     0.906     0.774     0.753
   0.740     0.771     0.741     0.765     0.778     0.825     0.848     0.846
   0.878     0.886     0.951     0.860     0.819     0.848     0.833     0.874
   0.851     0.827     0.799     0.811     0.772     0.778     0.828     0.847
   0.901     0.847     0.888     0.827     0.900     0.761     0.801     0.743
   0.741     0.707     0.703     0.779     0.764     0.775     0.920     0.912
   0.818     0.816     0.832     0.850     0.825     0.859     0.858     0.878
   0.876     0.873     0.888     0.920     0.931     0.886     0.875     0.853
   0.855     0.832     0.875     0.912     0.882     0.837     0.917     0.807
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     0.818     0.876     0.834     0.840     0.852     0.818     0.901     0.878
     0.855     0.854     0.859     0.888     0.853     0.824     0.786     0.804
     0.829     0.837     0.837     0.897     0.951     0.846     0.899     0.823
     0.870     0.945     0.960     0.876     0.858     0.873     0.793     0.851
     0.873     0.978     0.915     0.937     0.789     0.859     0.904     0.846
     0.800     0.862     0.785     0.820     0.836     0.867     0.971     0.809
     0.751     0.800     0.748     0.850     0.880     0.832     0.920     0.969
     0.846     0.720     0.769     0.842     0.887     0.925     0.895     0.937
     0.855     0.805     0.816     0.800     0.814     0.861     0.951     0.869
     0.794     0.731     0.816     0.838     0.866     0.937     0.967     0.949
     0.873     0.932     0.851     0.870     0.812     0.840     0.894     0.873
     0.790     0.891     0.878     0.816     0.858     0.843     0.981     0.940
     0.917     1.000     0.866     0.814     0.816     0.874     0.749     0.639
     0.812     0.991     0.921     0.782     0.937     0.831     0.883     0.917
     0.854     0.892     0.860     0.887     0.887     0.853     0.745     0.739
     0.848     0.979     0.822     1.000     0.776     0.825     0.904     0.906
     0.965     0.988
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  3880.664  4407.632  4458.660  4787.433  4797.453  4600.007  4120.648  4480.558
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   10.203     12.457      6.320      0.787      4.825      2.617      1.822      0.319
    0.332      0.569      1.388      3.839      3.702      4.136      0.841      1.305
    3.984      1.179      0.346      0.423      0.320      1.007      3.952      1.731
    0.590      0.966      6.726      6.212      3.251      0.388      1.767      7.885
    0.592      0.745
 5359.863   5688.148   6561.992   6726.355   4716.891   4418.652   4470.258   4479.535
 4751.516   5168.273   5329.066   5536.418   6547.926   6811.750   6803.648   6515.793
 6059.133   5946.840   5860.254   5818.348   6395.285   6877.480   6804.520   5295.703
 4844.613   5268.578   4951.293   4768.641   4901.270   5650.805   5523.246   5532.844
 5563.699   6222.957   6089.039   5304.258   5186.629   5403.684   5479.039   5328.777
 5065.102   6249.648   6990.770   7127.250   6657.328   6409.637   5656.371   5769.660
 6647.836   7204.191   7469.715   7473.594   7352.336   7115.891   6959.629   7336.344
 7476.668   7381.379   7621.145   7414.383   7334.086   7499.074   7236.090   6135.754
 6121.160   6517.695   7202.363   7320.734   7075.352   6282.387   5659.367   6227.539
 6784.809   7338.680   7170.375   6572.730   6812.238   7898.969   7567.121   7732.457
 7229.883   7303.203   7506.473   7809.570   7539.875   7616.016   7670.324   7732.340
 7679.789   7024.758   6530.402   5955.070   5804.230   6149.875   6748.168   6984.199
 6979.082   7283.109   7931.371   8076.301   8137.871   7906.078   7472.082   7157.809
 7456.379   7296.387   7184.180   7413.969   7594.602   7555.770   7352.023   7167.137
 7371.031   7024.102   7124.500   7408.723   7457.172   7907.836   8425.734   8442.891
 8397.141   8236.129   8109.238   8148.437   8150.547   8283.824   8607.852   7919.309
 7948.527   7782.410   7603.152   8224.410   8191.645   8113.930   8767.758   8590.437
 8385.234   7933.770   8112.770   8157.992   7899.594   7615.902   7695.609   7329.574
 7111.285   7430.930   7484.805   7619.887   8073.980   7767.598   8149.699   7942.430
 7484.746   7312.430   8139.949   7657.551   7533.656   8023.031   7916.973   8248.227
 8456.773   7911.742   7910.773   8286.695   8054.516   8446.711   7904.047   8006.719
 8051.590   8111.734   8672.945   8511.437   7937.074   8026.980   8064.906   7314.211
 7172.234   7778.113   7246.906   7823.852   8033.828   8120.164   7847.305   7812.555
 7612.547   7500.578   7621.980   7872.359   7780.195   7038.840   7214.680   7055.676
 6904.562   7334.477   7337.852   7252.727   7731.406   7522.094   7469.223   7047.305
 7492.859   7426.094   7384.020   7509.039   7437.426   6908.430   6482.023   6458.586
 6446.547   7223.926   7535.242   7093.656   6696.422   7397.156   6460.887   5851.910
 6089.328   6254.922   6492.477   5860.102   6032.348   6270.711   7118.867   6726.227
 5683.039   5787.109   6088.355   6770.586   7805.184   6690.336   5657.578   6612.137
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  6212.402  5745.551  5771.695  6197.914  7323.012  7402.449  7231.988  6738.133
  6428.273  5739.641  5842.367  5840.879  5997.723  6459.695  5706.117  4758.484
  4690.746  5601.930  6322.152  6285.121  6800.262  7113.973  7264.023  7015.832
  6455.687  6696.348  6213.141  5854.039  5677.031  5947.832  6686.859  6690.953
  5780.590  5732.281  5407.797  5575.625  5514.562  6404.789  6588.035  6673.324
  5342.922  5226.633  5103.184  4706.953  5340.715  4976.117  4839.344  5500.930
  6122.422  6620.082  7186.574  7554.059  6732.836  5731.562  5346.113  5550.945
  5075.309  4825.215  4758.594  5431.008  5605.648  5335.344  5526.586  5338.875
  5729.340  6006.320  4583.145  4200.000  4903.750  5178.578  5878.484  4487.641
  4974.980  5551.066
$STOP
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Definition of Notation

Representative units of variables are given in m, kgm, days, kcal and °C.

Small Roman Letters

a	constant in evaporation formula (m/day - millibar)
b	constant in evaporation formula (millibar^{-1})
c	specific heat (kcal/kgm°C) = 0.998
d_m	depth of layer for entrance mixing (m)
d_t	displacement of thermocline due to wind (m)
e_a	saturated water vapor pressure at air temperature (millibars)
e_s	saturated water vapor pressure at temperature of water surface (millibars)
g	gravitational acceleration m/day^2 = 7.315×10^{10}
h	mean depth of reservoir (m)
h_m	depth of mixed layer (m)
i	subscript denoting inflow
i_s	slope of water surface
i_t	slope of thermocline
j	number of grid point
jm	number of surface grid point
q	flow per unit width(m^2/day)
r	entrance mixing ratio
s	slope of reservoir bottom
t	time (day)
u_i	inflow velocity (m/day)
u_o	outflow velocity (m/day)
x	horizontal distance from outlet (m)
y	elevation (m)

y_b	elevation of reservoir bottom (m)
y_{mix}	elevation of bottom of mixed layer (m)
y_{out}	elevation of outlet (m)
y_s	elevation of water surface (m)

Roman Capitals

A	horizontal cross-sectional area (m^2)
A_b	average area of bottom element (m^2)
A_{ysur}	surface area (m^2)
B	width of reservoir (m)
D	coefficient of thermal diffusivity (m^2/day)
D_n	coefficient of numerical dispersion (m^2/day)
E_m	evaporation mass flux (kgm/m^2-day)
F_D	densimetric Froude number
H	heat flux (kcal/m^2-day)
L	length of reservoir (m)
L_t	length of reservoir at elevation of thermocline (m)
L_v	latent heat of vaporization (kcal/kgm)
N	ratio of heat conduction coefficient to mass transfer coefficient (kcal - millibar/kg°C)
Q	reservoir flow through rate m^3/sec
Q_{in}	inflow m^3/day
Q_{out}	outflow rate m^3/day
R	Bowen ratio
S_{area}	average area of surface element (m^2)
T	temperature (°C)
T_a	air temperature (°C) (unless otherwise specified)

T_i	inflow temperature
T'_{in}	mixed inflow temperature (°C)
T_m	temperature of mixing water (°C)
T_s	temperature of surface water (°C)
T_w	temperature of surface water (°K)
V	vertical advective velocity (m/day)
$\mathcal{V}$	volume of reservoir (m^3)
W	wind speed (m/sec)

Greek

α	coefficient of molecular conductivity (m^2/day) = 0.0125
β	fraction of solar radiation absorbed at the water surface 0.4 - 0.5
δ	thickness of withdrawal layer (m)
Δ	increment
ϵ	normalized density gradient (m^{-1})
η	radiation absorption or extinction coefficient (m^{-1})
ν	kinematic viscosity (m^2/day) = 0.0864
ρ	density (kgm/m^3) = 997
ρ_o	reference density (kgm/m^3) = 1000
σ_i	standard deviation of inflow velocity distribution
σ_o	standard deviation of outflow velocity distribution
ϕ	heat flux (kcal/m^2-day)
ϕ_a	longwave atmospheric radiation (kcal/m^2-day)
ϕ_c	heat loss flux due to conduction (kcal/m^2-day)
ϕ_e	heat loss flux due to evaporation (kcal/m^2-day)
ϕ_j	short wave radiation at element j (kcal/m^2-day)

ϕ_L	total surface heat loss flux (kcal/m^2-day)
ϕ_m	long wave radiation from sides of laboratory flume (kcal/m^2-day)
ϕ_o	net short wave radiation at water surface (kcal/m^2-day)
ϕ_{ra}	net longwave back radiation from water surface (kcal/m^2-day)
ϕ_{rw}	longwave radiation from water surface (kcal/m^2-day)
ϕ_s	shortwave radiation reaching water surface (kcal/m^2-day)
ϕ_{ysur}	shortwave radiation transmitted through water surface (kcal/m^2-day)
ψ	relative humidity

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